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TECHNIQUE FOR ESTABLISHING PERSONNEL PERFORMANCE STANDARDS (TEPPS). PROCEDURAL GUIDE: SECOND EDITION

M.B. Mitchell, et al

Dunlap and Associates, Incorporated
Santa Monica, California

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TECHNIQUE FOR ESTABLISHING PERSONNEL PERFORMANCE STANDARDS (TEPPS)

PROCEDURAL GUIDE

SECOND EDITION

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WESTERN
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PSYCHOLOGICAL RESEARCH BRANCH (PERS-A32)
PERSONNEL RESEARCH DIVISION
BUREAU OF NAVAL PERSONNEL

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TECHNIQUE FOR ESTABLISHING PERSONNEL PERFORMANCE STANDARDS (TEPPS)

PROCEDURAL GUIDE

SECOND EDITION

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Prepared for:

Psychological Research Branch (Pers-A32)
Personnel Research Division
Bureau of Naval Personnel

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FOREWORD

This is the second edition of the procedural guide for applying TEPPS (Technique for Establishing Personnel Performance Standards). Since the first edition was published in January 1966, additional methodological work has been performed and a field test was conducted on a Navy CIC system. This edition incorporates the results and findings of those efforts. For detailed technical discussion of the development and test of TEPPS, the reader is referred to the documents in the bibliography.

The study to develop and test TEPPS was performed under the cognizance of the staff of Captain R. G. Black, USN, Director, Personnel Research Division, Bureau of Naval Personnel. Dr. Martin Wiskoff, Head, Psychological Research Branch (Pers-A32) was Scientific Officer.

Responsible officer for Dunlap and Associates, Inc., was was Dr. Joseph W. Wulfeck. Dr. Robert E. Blanchard was Project Director. Staff members were Dr. M. B. Mitchell, Mr. R. L. Smith, and Mr. R. A. Westland.

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I. INTRODUCTION

A. General Remarks

Every system is presumed to be designed to accomplish a well-defined mission; therefore its success can be stated objectively in terms of specific criteria. For example, a radar system may be designed to detect and identify the type, range, and bearing of a target within certain range and height limits, and also to determine its closing rate. However, no system performs perfectly at all times. As a result, system designers need to know the operational requirements for successfully satisfying the criteria for mission accomplishment. (It may be critical that the above radar system accurately performs its mission 90 percent of the time and within five minutes for each target.) System Effectiveness Requirements (SERs) for probability and time imply that each man/machine operation must meet minimal standards for the SER to be met. TEPPS, then, is a method for deriving probability and time standards for identifiable man/machine activities so that the system can meet its overall SER.

The organization of this guide follows the general outline of approach shown in Figure 1. That figure describes the major procedural steps performed in applying TEPPS for operator or scheduled (preventive) maintenance tasks. Starting with effectiveness requirements and system descriptive data, the sequence of steps begins with a description of the methodology analyzing the system so as to represent it graphically. The graphic model can be converted to a mathematical model for use in allocating the system effectiveness requirements to definable system segments. However, if TEPPS computer program is utilized, construction of a mathematical model is performed implicitly by the computer, which then derives man/machine performance standards based on the results of analyzing the mathematical model and the system operational requirements. Since the procedure for establishing standards for corrective maintenance tasks differs from that for operator tasks, it is described separately in Section V of this guide.

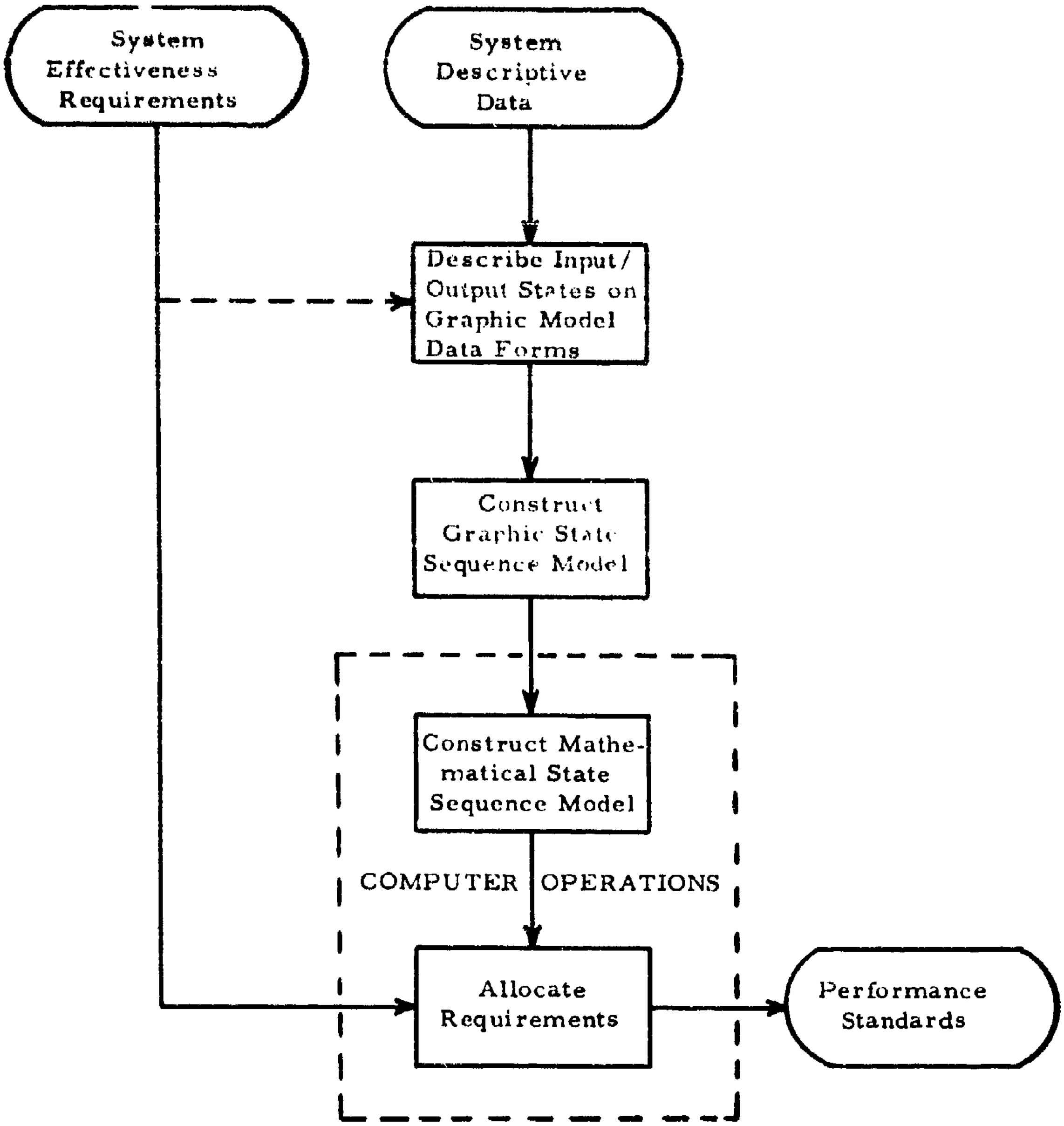

Figure 1. Outline of TEPPS approach.

Use of the procedures included here rests primarily upon three basic assumptions:

1. The user has experience in systems analysis, in general,

2. The user is familiar with the specific system being analyzed to the extent that he can fully utilize the available data describing the system, and

3. The procedures are to be applied to analysis and evaluation of existing systems in contrast to system conception and initial design.[1]

The requirement for familiarity with the specific system is important because the analyst must be able to perceive the system's capabilities objectively without being constrained by the performance expected of it. That is, he will be called upon to recognize if the system might perform in ways other than those (1) recorded in documents such as operational procedures, or (2) carried out in actual practice.

Accurate application of TEPPS primarily depends upon a knowledge of general procedural rules which may apply at any time throughout the construction process. In order to facilitate understanding, examples are presented frequently. However, since each system (and therefore each application) is unique, examples should not be taken literally, but used as an aid to understanding the basic rules of system analysis.

B. Definitions

Several concepts and terms which are frequently used in this guide are defined in this section. Some of the terms have been developed specifically for TEPPS. It is especially important that all definitions be thoroughly understood before proceeding further.

[1] Since the procedural guide can be modified to include use of TEPPS for design, and since the technique has the potential as an evaluative aid in design, there are times throughout the guide when reference is made to the difference in applying TEPPS to existing systems as opposed to those in the process of being designed.

- System - A System is an operational set of components delineated by its input state, required output state, and constraints. A system includes all features of that set which are affected by the transition from input state to output state within the constraints imposed upon it. A system can be represented graphically by a single complex Personnel/Equipment Function Unit (PEF Unit) indicated by a rectangle, as shown in Figure 2.

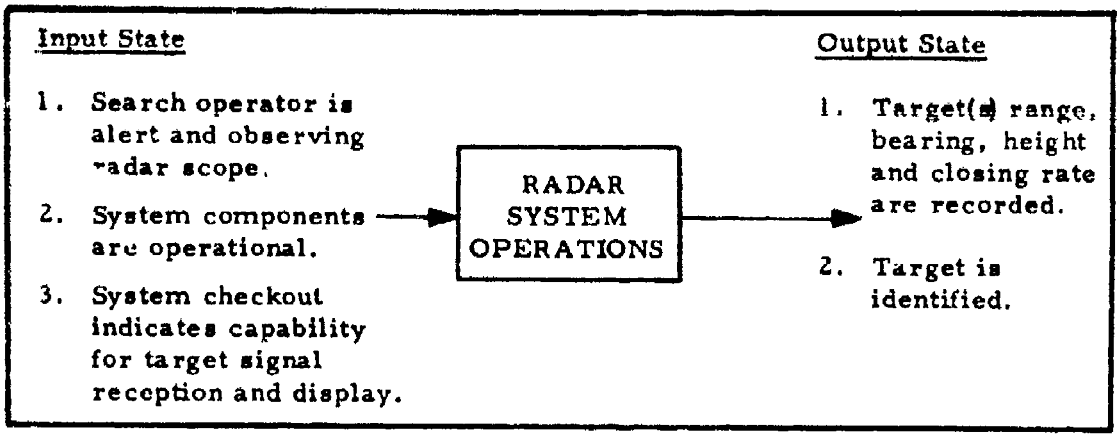

Figure 2. A PEF Unit at its most general level.

- PEF Unit - A Personnel-Equipment Functional Unit is a general term indicating man-machine or man-man interaction at any level of specificity, depending upon the context of discussion. As opposed to a state, a PEF Unit represents one or more operations, activities or processes. The PEF Units of Figure 3 are much more specific than that of Figure 2, in that they describe more detailed operations that must occur to meet the required system output.

- State - A state of a system is identified by a complete description of the relevant and measurable characteristics of the system at an instant in time. The description of the state is always a declarative sentence including the word "is" or "are"; e.g., in Figure 3 one of the system input states is "Search Operator is observing radar scope." States are represented graphically as lines leading to or from boxed PEF Units.

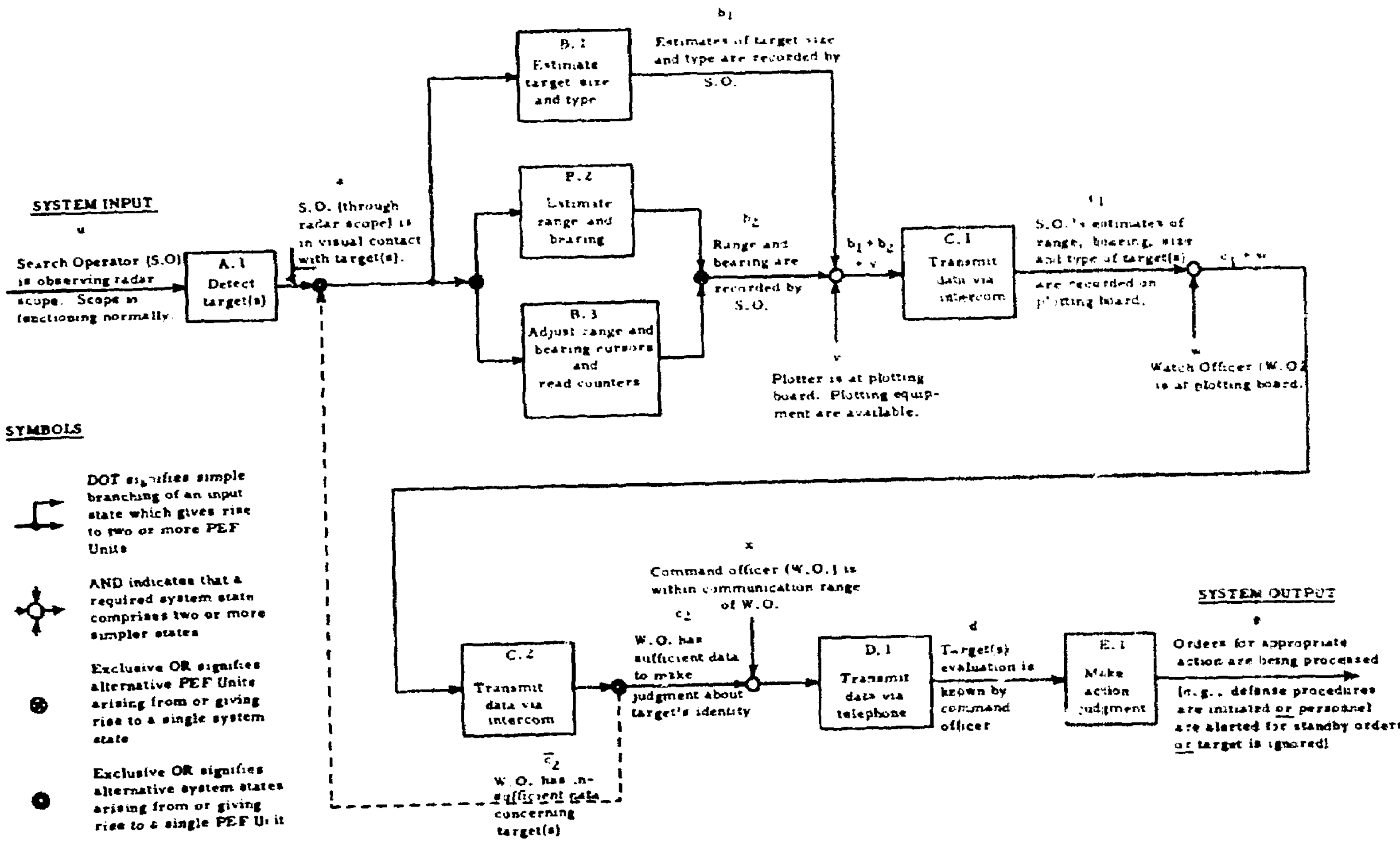

FIGURE 3. EXAMPLE OF A GRAPHIC STATE SEQUENCE MODEL AT A DETAILED (OR ELEMENTAL) LEVEL.

- Input State - The input state of the system is specified by initial system conditions which can undergo change during system performance; a change may occur at any time in the system's operation until the output state is reached.

- Intermediate States - Intermediate states (between two or more PEF Units) are all the instantaneous conditions of the system which have undergone change as a result of the immediately preceding operation(s) (i.e., prior PEF Unit). While only changed features are actually described for intermediate system states, all prior unchanged conditions are assumed. That is, the description of a state implicitly includes all unchanged portions of the system input state and the last described condition of all features which have been altered from the system input state.

- Output State - The output state of the sytem is specified by the overall system requirements. It includes objective statements indicating the accomplishment of the system's objectives. In Figure 3 the required system output state is "orders for appropriate action are being processed."

- Function - The broadest description of system operations (next to a general statement of the system itself) is made in terms of Functions. A Function is a PEF Unit delineated by an input state, required output state, and constraints without regard to the specific hardware of personnel of the system. Frequently, a single verb such as "detect", "evaluate", or "calibrate" suffices to define a Function.

- Element - An element is alternatively called an elemental PEF Unit. It represents the most specific level of system description to which these procedures are designed to be applied.

- PEF Unit Relations - The relations among PEF Units are determined by required sets of input and output states, possible alternative output states or alternative ways of making the transition from a given input state to a subsequent output state. Refer to Figure 3 for examples of the following.

1) The input state of the PEF Unit may be:

   a) The system input state (states u, v, w, and x).

   b) Identical to the output state of an immediately preceding PEF Unit (state d, input to E. 1).

   c) Made up of more than one component, each of which represents the output state of another PEF Unit (input to C. 1).

2) Somewhat overlapping the above, the output state of the PEF Unit may be:

   a) The system output state (state e).

   b) Part of the input state to a subsequent PEF Unit (C. 2 is part of the input state to D. 1).

   c) All of the input state to a subsequent PEF Unit (state a is adequate for B. 1 and B. 2 or B. 3).

- GSSM - The Graphic State Sequence Model (GSSM) is a diagrammatic representation of the system in detailed form. It specifies not only what the system is expected to do but also what the system is capable of doing. To construct an accurate model, therefore, the constructor must be thoroughly familiar with the system and all documents associated with it. Figure 2 illustrates the simplest form of GSSM, but it has very little analytical value. Figure 3 is an example of a hypothetical system in more detailed GSSM form. The GSSM may include a maximum of eight symbols. Their explanations and the rules for constructing a GSSM are presented in Section II.

- MSSM - The Mathematical State Sequence Model (MSSM) is a set of one or more equations which express the relation between the required probability of achieving the system output state (i.e., the probability component of the System Effectiveness Requirement or SER) and the probabilities of accomplishing the PEF Units which the system comprises. When stated explicitly, the MSSM directly reflects, in equation form, the structure of the GSSM.

- Allocation - Allocation refers to the process of resolving the MSSM and thus distributing the SER (System Effectiveness Requirements) among the PEF Units, thereby specifying the probability and time standards of performance for those units. Allocation is the first goal of TEPPS.

- TEPPS Computer Program - The set of instructions for the computer to perform the mathematical manipulations for deriving standards based upon input data concerning (1) effectiveness requirements, and (2) PEF Unit parameters and their contributions to the GSSM.

- Effectiveness Dimensions - Effectiveness is broadly defined as the degree to which a system (or a functional unit of a system) achieves its stated objective. Effectiveness dimensions are related directly to stated system objectives and provide for measurement of system (or functional unit) effectiveness. A numerical value on an effectiveness dimension reflects the degree to which the corresponding objective was fulfilled. Among the dimensions of effectiveness that may be appropriate are (1) probability of success, (2) performance time, (3) performance accuracy, and (4) quantity or quality scales. A composite of effectiveness dimensions may be necessary in order to reflect the system objective adequately. Dimensions used to characterize overall system effectiveness may or may not translate directly to the dimensions that characterize effectiveness of any particular system subdivision or lower-level functional unit.

- Effectiveness Requirement (ER) - An effectiveness requirement is a stipulated value or magnitude on a given effectiveness dimension that must be met or exceeded by a system functional unit. When the functional unit is the entire system, the effectiveness requirement is identified as the System Effectiveness Requirement (SER). For example, an effectiveness dimension of detection range might be established for a surveillance system; a value of 100 miles might then be stipulated as the SER. Effectiveness requirements also may be stipulated for major functions the system is to perform. For the example above, effectiveness requirements may be stipulated for such major functions as target identification, classification and threat assessment (effectiveness dimensions). When the functional unit is a PEF Unit at a subsystem level (or lower), effectiveness requirements are not stated but are derived from those stated at the function or

overall system level using an allocation model. Effectiveness requirements may take the form of a single value on an effectiveness dimension, or under certain circumstances several values may be defined representing levels of effectiveness (degrees of system success) which are acceptable under specified conditions for that system. For cases in which more than one effectiveness dimension is required to reflect the system objective, the ER is a series of numerical values such as a required probability for meeting the system objective within a given accuracy tolerance within a given time. In some instances, the ER may represent an index resulting from the mathematical combination of values on several effectiveness dimensions.

- Redundancy - Redundancy refers to a duplication of system operations. Redundancy occurs when there are two or more PEF Units (or two or more sequences of PEF Units) within a system that give rise to essentially identical outputs, the occurrence of only one of which is necessary to mission success. Redundancy PEF Units (or sequences of PEF Units) may have the same or different effectiveness levels and may or may not involve the same operations.

- Personnel Performance Standard (PPS) - A personnel performance standard comprises a description of a Personnel-Equipment Functional Unit (PEF Unit) and an associated numerical value established on an appropriate performance dimension for that PEF Unit. The performance dimension is related directly to the system effectiveness dimension and to the System Effectiveness Requirement (SER). Meeting or exceeding the derived personnel performance standard is necessary for the SER to be realized. Among the dimensions that may be appropriate are (1) performance accuracy, (2) performance time (3) quantity or rate of output, and (4) quality of output. The type of PEF Unit outputs are many and varied, but may be classified as (1) true dichotomous distributions, (2) artificially dichotomous distributions, and (3) continuous distributions. For all types of dimensions, a probabilistic statement can be made relative to the achievement of a particular value on that dimension. In general, the current state-of-the-art is represented by the probabilistic approach. Examples of various forms of PPS are:

Accuracy:	"Adjust amplifier balance to zero within ± 5 mv"
Time:	"Remove and replace defective circuit card within 2.5 minutes"
Rate:	"Log and file 25 incoming messages per hour"
Quality:	"Expose oscillograph paper to light and judge the acceptability of the resultant traces"

The above dimensions could be treated as artificial dichotomies, i.e., the required performance level was or was not achieved (pass/fail). Or, a probabilistic statement could be made concerning the required performance level; for example:

> "Adjust amplifier balance to zero within ± 5 mv with probability = .90"

Such a requirement statement indicates that personnel assigned to perform the PEF Unit could fail to achieve the required accuracy level 10 times in 100 and the SER could still be realized.

C. TEPPS Input Data Requirements

The three general types of input data required for full employment of TEPPS are discussed below along with potential data sources.

1. System Effectiveness Requirements (SER)

SERs established for the system specify the extent to which the system is expected to achieve stated mission requirements. They constitute a quantitative description of what functions the system is to perform and how well it must perform them. SERs represent the ultimate criteria against which system performance is measured and are used as the basis for establishing personnel performance standards. Three major classes of requirement measures are:

a. General. Overall effectiveness requirement, e.g., probability of accomplishing the mission for which the system was designed, where the mission may be defined along one or more dimensions such as number of radar target, identifications, accuracy and time to make them.

b. Performance. Required ability of the system to achieve specific operational objectives given that the system is operating. This class of requirements is usually associated with major system functions, e.g., for a radar system, probability and/or time requirements for such functions as detection and tracking.

c. Availability/Dependability. Required expectancy for system operation at a given point in time during the mission (system duty cycle). For example:

$$A = MTBF/(MTBF + MTTR)$$

where:

MTBF = Mean Time Between Failures

MTTR = Mean Time To Restore

The level of detail and completeness of SER input data will vary as a function of the type of system under study, the particular step in the RDT&E process at which TEPPS in introduced and the degree to which system requirements studies have been performed. Usually, operational requirements evolve in hierarchical fashion. Early in the life of a system, they are likely to be stated in rather gross terms. As system design and development proceed, requirements data evolve to more specific and detailed statements.

To be most useful in design trade-off analyses, TEPPS must be introduced early in the design process; however, its application depends upon the availability of SER data. The Proposed Technical Approach (PTA) stage is a likely start point for TEPPS application. If system requirements data are not on hand, then TEPPS must await requirements determination studies performed as part of PTA prep ration.

In instances where requirements documentation is limited, consideration should be given to using interviews with representatives of Navy "purchaser" of the system. Estimates of system requirements obtained from expert judges can be used as starting points for TEPPS analysis. Based on feedback from TEPPS use, these data can be modified, refined, or revised as need be by the originator. Limited documented requirements data need not necessarily preclude TEPPS application. It may increase the liaison effort required with certain Navy activities; however, considering the potential gain, such additional effort would seem to be justified.

General sources of system requirements data include:

- Mission requirements studies.
- System effectiveness studies.
- Enemy capability analyses.
- Interviews and liaison with representatives of CNO, CNM, and the Principal Development Activity.

Sources specific to the Navy's RDT&E documentation process are:[1]

- Task reports resulting from research on an exploratory development requirement (EDR) or a general operational requirement (GOR).
- Tentative Specific Operational Requirement (TSOR).
- Proposed Technical Approach (PTA).
- Advanced Development Objective (ADO).
- Specific Operational Requirement (SOR).
- Technical Development Plan (TDP).

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[1] For further information on these RDT&E documents, see OPNAV Instruction 3900.8B, Planning Procedures for the Navy Research Development, Test and Evaluation (RDT&E) Program.

2. System Descriptive Data

This type of input data includes any and all information that serves to describe the functional design of the system and its manner of operation. System descriptive data help define the design approaches to fulfilling the SERs imposed on the system and the allocation of system functional requirements among man and machine. These data provide the basis for constructing the Graphic State Sequence Model (GSSM) for TEPPS. Typical sources of system descriptive data are:

- System predesign reports and memoranda.
- Mission analysis reports.
- Function definition and system flow diagrams.
- System design specifications.
- Development and test reports.
- Operating and maintenance procedural documents.
- Personnel planning information documents.
- Liaison with engineering design personnel.

Similarly to SER data, system descriptive data evolve in level of detail and comprehensiveness as system design and development proceeds. In the early stages of system design, such information is likely to be stated in rather general terms with limited documentation. Full utilization should be made of liaison with cognizant design personnel to obtain information necessary for TEPPS application as early as possible in the design process.

3. Human Capability Data

Human capability data are necessary in order to determine the effect on system effectiveness of personnel performance levels that deviate from established performance standards. Such data represent available personnel capabilities (resources), and when compared to established performance standards provide an estimate of the degree to which system effectiveness requirements can be fulfilled. At present, no comprehensive and fully reliable store of human performance data is available. In the absence of an applicable data store,

capability data can be obtained on the specific personnel group being considered for assignment to the system by measuring the performance of that group on the man-machine activities resulting from the standards allocation process. Other sources would be (1) proximate data obtained from previous studies of personnel activities comparable to those required by the system under study, (2) simulation studies involving the personnel activities under study, and (3) judgments made by experts intimately familiar with the performance of the personnel group under consideration on identical or similar activities in other systems.

Subjective judgment techniques (method of paired comparisons), in conjunction with an appropriate transformation equation, have been employed successfully to obtain estimates of the probability of accomplishing man-machine activities[1]. Human capability data derived in that manner have been used in an application of TEPPS to a Navy CIC subsystem[2].

In order to apply TEPPS Computer Program for allocation of requirements so as to derive standards, it is currently necessary that human capability data be available in the following form.

(1) Activity description, consistent with the description of a system -- required activity.

(2) An identification number associated with that activity description.

(3) Estimated maximum probability with which the activity can be performed correctly by a given population.

(4) The "minimum" time and "maximum" time to accomplish the activity by the assumed population. These time values are assumed to be, respectively, at minus and plus three standard deviations from the mean of a lognormal distribution of performance times.

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[1] Blanchard, R. E., Mitchell, M. B., & Smith, R. L., Likelihood-Of-Accomplishment Scale For A Sample Of Man-Machine Activities, Dunlap and Associates, Inc., Santa Monica, California, June 1966.

[2] Mitchell, M. B., Smith, R. L., & Blanchard, R. E., Test Application Of TEPPS On A Navy CIC Subsystem, Dunlap and Associates, Inc., Santa Monica, California, August 1967.

II. CONSTRUCTING THE GRAPHIC STATE SEQUENCE MODEL (GSSM)

A. Introduction

The principal purpose of constructing a diagrammatic representation of a system is to provide a clear and complete basis for performing a logical, objective analysis of a system. By reducing the system to its sequence of instantaneous states and transitional PEF Units, the GSSM establishes a framework which permits the analyst to view an existing system not only as it was designed to operate, but also as it is potentially capable of operating. If complete, the GSSM provides all necessary information for representing the system symbolically to a computer so that it can perform the necessary operations to allocate system effectiveness requirements and derive performance standards. Alternatively, the GSSM enables construction of a corresponding Mathematical State Sequence Model (MSSM) which enables manual derivation of standards and which can aid interpretation of the results of allocation.

A MSSM generated either by the computer or an analyst is a direct reflection of the GSSM. Therefore, it is particularly important that the GSSM represent the system completely and include all necessary states and all important operations -- in the form of PEF Units -- of which the system is capable. An accurate GSSM not only maps the system correctly but also permits the evaluation of alternative approaches to reaching a given output state. For example, even though the procedures call out a specific activity (PEF Unit) which may be sufficient to achieve a particular output state, another PEF Unit may be more appropriate in terms of overall probability of accomplishment and/or time constraints.

B. Symbols Used in the Graphic Model

The GSSM comprises nine primary components to symbolize the system process, states, and their interrelations. Definitions of the symbols appear in Table 1. Figure 4, which follows Table 1, elaborates on some of the definitions by illustrating representative examples in which the symbols are used.

C. Preliminary Procedures

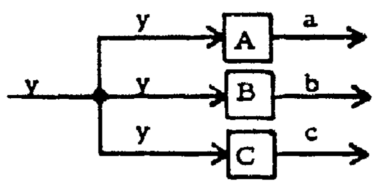
Preparations for constructing the actual graphic model include gathering and organizing all necessary available information. It can usually be expected that additional data might be needed as GSSM development progresses, since proper construction generally reveals facets of the system not otherwise apparent. To minimize later footwork, the following data should be gathered before beginning the GSSM.

Table I

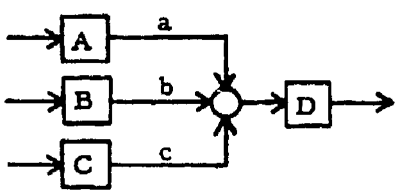
Definitions of GSSM Components

Rectangle symbol indicates a PEF Unit that must occur for the system to change from state y to a required state z.

An arrowed line indicates (1) a transient state, i.e., all relevant measurable characteristics of the system at an instant in time, and (2) the direction toward which that state leads.

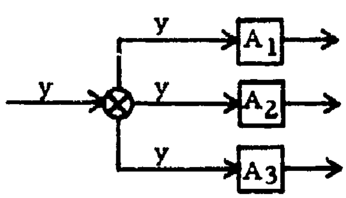


Dot symbol indicates that a single state is necessary and sufficient to give rise to two or more independent and system-required PEF Units which may occur either simultaneously or in any order.



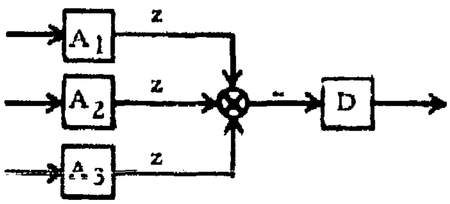
The open circle is an AND symbol indicating that two or more independent states must exist simultaneously to become the effective input state for a subsequent PEF Unit. In the accompanying figure the necessary and sufficient input state for D is the simultaneous existence of state a and state b and state c.

Circle with X symbol indicates that a single state is associated with only one of two or more mutually exclusive PEF Units:



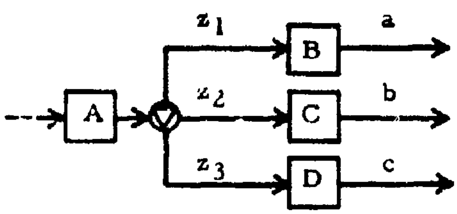
As an input symbol, it indicates that the state is necessary and sufficient to give rise to one, and only one of two or more alternative, mutually exclusive occurrences. In the adjoining figure, state y can lead to the occurrence of either A_1 or A_2 or A_3.

Table I (continued)

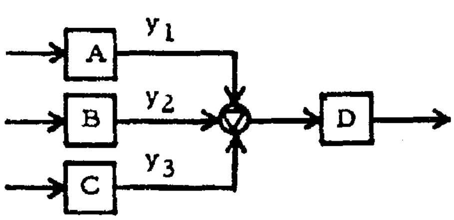


As an output symbol, the circle with X indicates that a given state may arise from one and only one of two or more alternative, mutually exclusive occurrences. In the adjoining figure, state z may result from either A_1 <u>or</u> A_2 <u>or</u> A_3.

<u>Circle with triangle</u> symbol indicates that only one state may exist from among two or more possible states at the same point in the system's operation:



As an input symbol, it indicates that a single PEF Unit may give rise to one and only one of two or more alternative states, each of which may -- at one time or another -- be normal to the system operation. In the figure, either state z_1 <u>or</u> z_2 <u>or</u> z_3 will result from PEF Unit A under normal operating conditions.

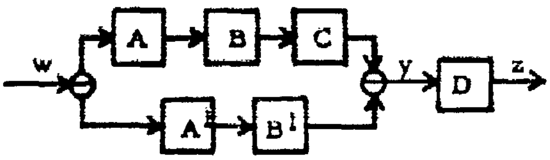


As an output symbol, it indicates that there are two or more mutually exclusive states each of which are both necessary and sufficient to give rise to a given PEF Unit. In the adjoining figure, activity D depends upon either state y_1 <u>or</u> state y_2 <u>or</u> state y_3.*

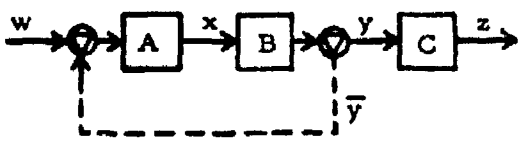
---

* The <u>circle with X</u> input symbol differs from the circle with triangle symbol in the following ways: The input ⊗ usually indicates system capabilities in the sense that only one of the PEF Units following that symbol need ever occur -- the others conceivably could be eliminated. The ▽⃝ symbol indicates that the system may always be expected to assume one of two or more states as a result of a particular PEF Unit. (See examples in Figure 4.) It may be noted that the ▽⃝ symbol is implied for the output of every PEF Unit in the system, in that the required state may not arise, possibly due to a failure condition. Since it is always implied, the symbol usually is omitted with the understanding that if the specified state does not occur, maintenance activities will ensue. It is where there are possible states other than those leading to maintenance that the ▽⃝ symbol is used.

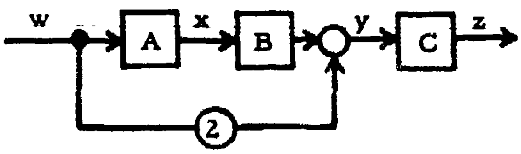
Table I (Continued)



Horizontally split circle symbol indicates redundant procedures to produce the transition between w and y. In effect, A+B+C increase the likelihood of the functional accomplishment of A+B; or vice versa.



Dashed line symbol indicates a state which leads to a repetition of a previously performed set of activities in a cyclical manner. In the accompanying figure, the sequence A-then-B is to be repeated if state $\overline{y}$ exists.



Arrowed line with circle symbol indicates simultaneous identical operations -- and intermediate states -- in two or more independent subsystems. In the accompanying figure, the sequence A-then-B occurs in three different parts of the system (A→B and two more in parallel); the input state for C is the summation of the output states of the three subsystems.

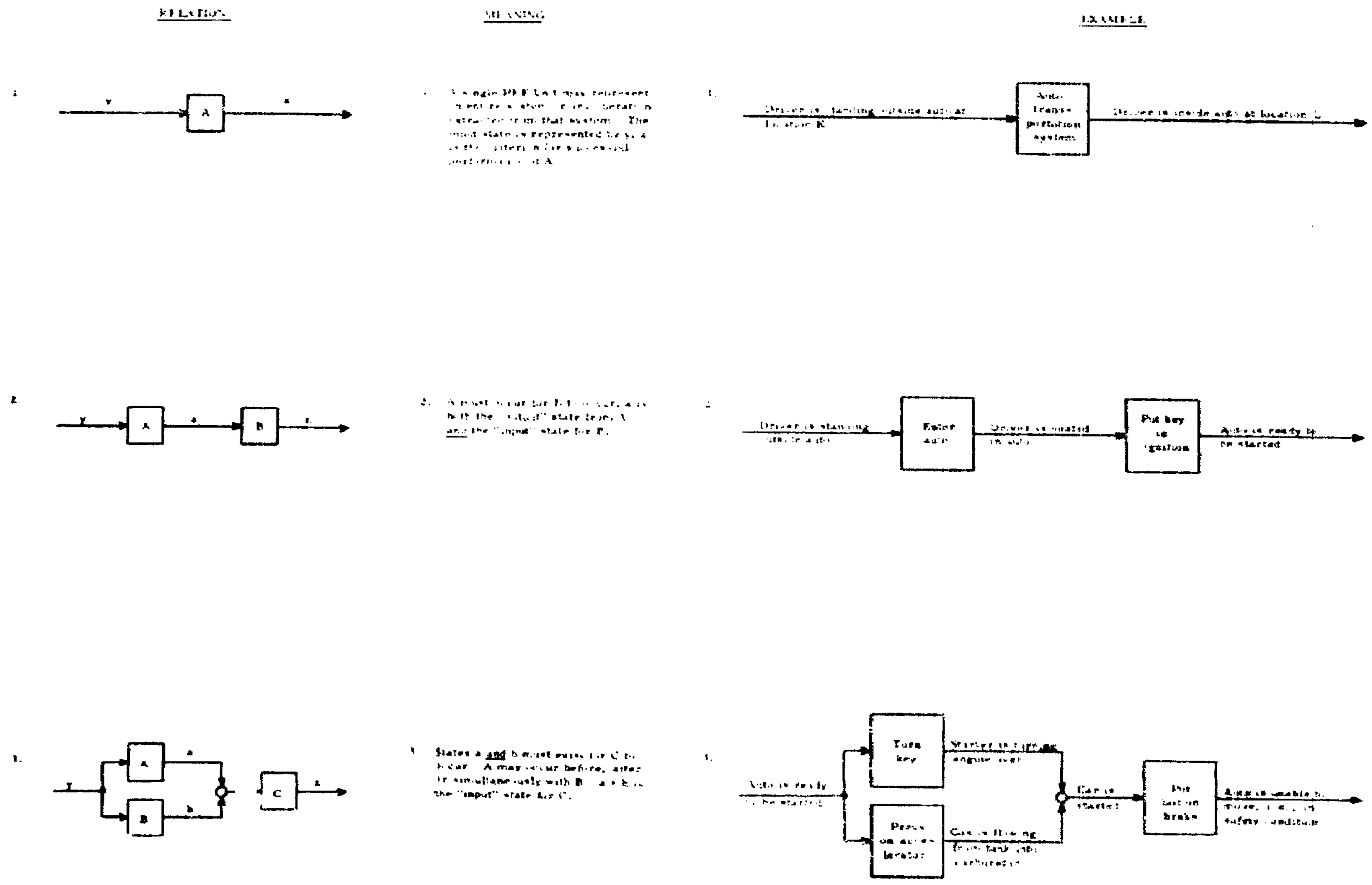


FIGURE 4. SOME BASIC CONSTRUCTIONS.

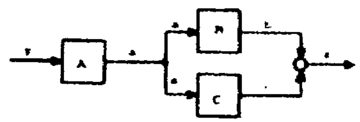
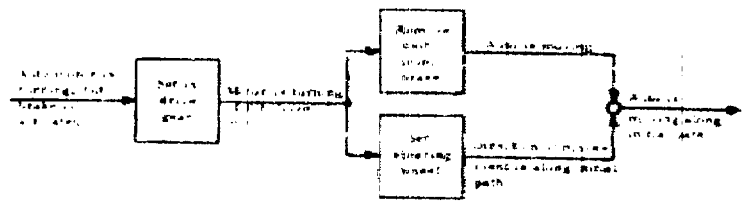
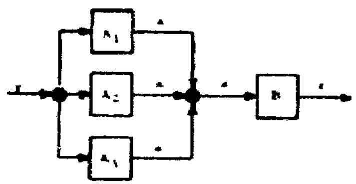
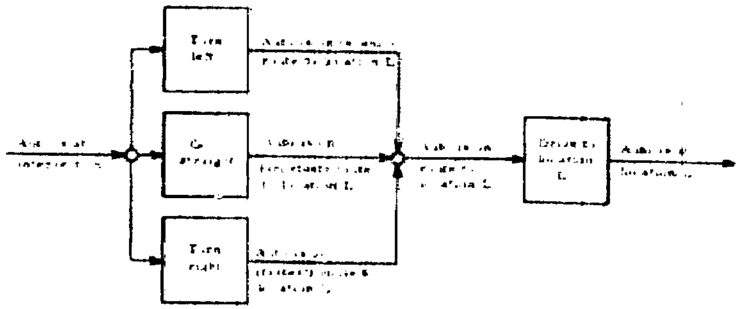
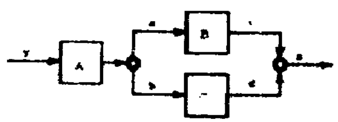
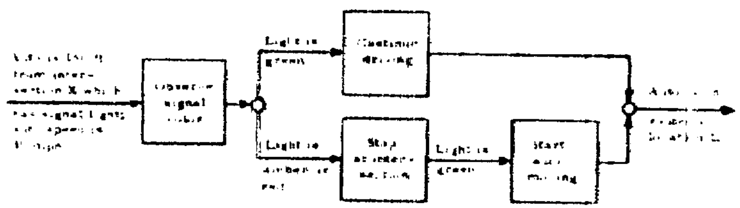
RELATION	MEANING	EXAMPLE
4. 	4. [illegible]	4. 
5. 	5. State y is adequate for either A_1, or A_2 or A_3 [illegible] that is, state a may be reached by any one of the three processes, A_1, A_2 or A_3 although not necessarily with the same [illegible] with the same degree of certainty.	5. 
6. 	6. [illegible]	6. 

FIGURE 4 (CONTINUED)

1. Overall system effectiveness requirements

   - The precise final output state of the system

   - Probability required for the final output state[1]

   - Time limitations from onset to completion of system functioning (if applicable)

2. Specific system effectiveness requirements

   - The precise output state at any intermediate stage of system operation for which effectiveness requirements have been established (if applicable)

   - Probabilities required for intermediate system states (if any are available)

   - Time limitation for the transition from one intermediate state to another (if any are available)

3. Input state conditions, i.e., complete description of the relevant system just prior to its initiation

4. System constraints, either specified or assumed.

Each of the above types of data will be illustrated later in an example.

D. Alternative Construction Procedures

There are two primary ways to begin constructing a GSSM: (1) List all states and PEF Units in sequential order on data forms before proceeding to the GSSM, or (2) Begin immediately to construct the GSSM on a "trial and error" basis; i.e., start with a rough model and continue to refine it until it completely and accurately represents the system. The first method has the advantage of aiding or organizing and preserving the logical step-by-step procedures employed in this guide, while the second may enable some analysts to conceptualize PEF Unit interrelations more easily. However, since it cannot be predicted which method may be more satisfactory for a given analyst it is recommended that he proceed via the Graphic Model Data Form (GMDF) technique upon applying TEPPS for the first time.

[1] Tolerances, or accuracy requirements associated with the final or intermediate system states are assumed optimal when considering probability requirements.

Generally, the information necessary for constructing the Graphic Model Data Forms or the GSSM is likely to be available in the form of operational procedures for a system which already exists. However, some operations may occur which are not specified formally, and it is therefore necessary for the analyst to include that information through observation and/or general knowledge of the system.

E. Organizing Data on Graphic Model Data Forms

The purpose of the Graphic Model Data Form (GMDF) is to organize existing information regarding the human contribution to system performance in a format that will facilitate subsequent GSSM construction. The GMDF does not guarantee complete information about a system; the analyst will need to exercise considerable care in constructing the GSSM whether or not Data Forms are utilized. The Forms only organize existing data, and do not indicate errors or omissions.

Figure 5 illustrates the recommended headings for the GMDF columns. The meaning of those headings will be clarified in the following discussion.

Graphic Model Data Form

Function ______________________

Probability __________ Time ______

PEF Unit No.	Prior Necessary Step(s)	Alternate Step(s)	Activity Description	Output State	Imposed Requirement (SER)	
					P	T

Figure 5. Recommended headings for the GMDF.

Step 1: Analysis at the Function Level

On the first GMDF, cross out "Function" and write "System" at the top. This data form will contain the initial breakdown of the system into Functions and inter-Function states. Following "Probability" and "Time," list the overall system effectiveness requirements which were prepared in Section II. C. Divide the system into Functions by specifying as many gross system states as can be identified; if possible, assign general activity states to the mediating PEF Units in accordance with the definition of a Function in Section I. B.

a. Assign a capital letter to each Function, starting with "A" and place those letters under the heading "PEF Unit Number."

b. Under "Prior Necessary Step(s)" list the letter code for the Function(s) required in order that the needed input state exists. For example, if PEF Units B and C are parallel Functions coming after A, then the prior necessary step for both B and C will be "A," because A provides the required input state for C as well as for B. (See relation No. 4 in Figure 4 on page 17).

c. List whether alternate Functions exist ("yes" or "no"). In the examples above, state "no" for all three functions. However, if B and C are mutually exclusive, then "yes" should be indicated in the column headed "Alternate Step(s)" for both B and C. (See relation No. 5 in Figure 4.)

d. Under "Activity Description" name the Function in a single word verb, or a brief verb phrase, indicating the general operation, e.g., "detect," or "checkout of equipment X."

e. Specify the output state of each function in relation to its input state, i.e., describe only those conditions which have been altered from previously specified and implied conditions.

f. Under "Imposed Requirements (SER)" enter probability (P) and, if applicable, time (T) components of the system effectiveness requirements, under P and T, respectively. Those values will have been listed according to the procedures in Section II. C.

Example of Step 1

The following hypothetical example illustrates the technique in skeletal form in order to be brief. A more complete example would give detailed data.

System:

Bench checkout of electronic item X (a relatively complex electronic device)

a. Requirements:

   1) The list of criteria to be met. a realistic example, those output state criteria would actually be stated. In effect, the output state describes conditions such that X is ready for installation.)

   2) Time limitation for entire checkout (if applicable).

   3) Probability required for successful checkout.

b. Input state conditions:

   1) Checkout equipment are available. (These should be itemized.)

   2) X is on bench.

   3) Technician has checkout procedure manual open to first page of instructions.

   4) Required power is available at the bench (specify; e.g., 10 V.D.C; 115 VAC, 60 cps).

c. Intermediate characteristics: (In checkout procedures, these are generally specified by the output criteria, as listed under "Requirements" above.)

d. Constraints:

   1) Environmental conditions (temperature, noise, illumination, etc.) are within tolerance range of technician and hardware.

   2) Checkout table is not made of any material which conducts electrical current.

   3) Technician stands on rubber mat during checkout.

e. Established Functional code designations and states (see Figure 6).

A ⟶ Necessary items of checkout equipment are set up for maximum effectiveness.

B ⟶ All equipment are activated.

C ⟶ Checkout measurement requirements are satisfied.

D ⟶ X is ready for installation.

Graphic Model Data Form

SYSTEM
~~Function~~ Bench Checkout of X

Probability P_o Time T_o *

PEF Unit No.	Prior Necessary Step(s)	Alternate Step(s)	Activity Description	Output State	Imposed Requirements	
					P	T
A	Input	--	Set up equipment	(Every piece of equipment should be listed, each with its required location)		
B	A	No	Supply power to equipment	(List all activation conditions and indications that equipment is on)		
C	B	No	Checkout X	(List of measurement data specified in a. 1), 2) & 3))		
D	C	No	Secure equipment	X is ready for installation		

Figure 6. Example of GMDF indicating gross Functions.

* Note that P_0 and T_0 are the probability and time components of the overall system SER; all intermediate values are represented by P and T.

Step 2: Analysis at the Element Level

One may proceed directly to the elemental level of system description, or one may describe PEF Units at a level of specificity intermediate between Functions and elements, depending upon the complexity of the system. For large complex systems, intermediate levels may need to be generated in order to be able to manage further analysis accurately down to the elemental level. For example, "Bench Checkout of X" may be considered a subfunction of "Checkout" of a very large system which involves design, construction and checkout of many pieces of equipment.

The notation which is used to designate levels of specificity is illustrated in Figure 7 below. Note that the first level (left hand letter) refers to Functions and the last level (right hand number) to Elements; intermediate levels are designated by additional numbers between those two.

Systems may be analyzed to two or more levels, and different numbers of levels may be used for different systems. As a rule, for any one system, the same number of levels should be used throughout the analysis so as to avoid confusion; as a result, there may be some Functions with intermediate zero designations, indicating direct breakdown to the element level. In the example to be presented later in this section, only two levels of specificity are indicated; B. 3, for example will represent the third element of Function B.

Levels of Specificity	1 Function	2 Intermediate	3	4 Element
Example of PEF Unit Notation	C .	1 .	2 .	5
Explanation	(Third Function)	(First gross operation under function C)	(Second activity under the first gross operation under function C)	(Fifth element under the second activity under the first gross operation under function C)
Example	Checkout	Bench checkout of X	Supply power to equipment	Place ON-OFF switch on X in ON position

Figure 7. The four levels of specificity of a hypothetical four-digit PEF Unit (C. 1. 2. 5). (Designation of the fifth element under the second activity under the first operation under the third function of the system.)

1. At the top of the GMDF, identify the Function to be analyzed (with its name and code letter).

2. Referring to the operational procedures, assign a number to each procedural step. (For Function A, the first step would be A. 1, the second A. 2, etc.)

3. Under "Prior Necessary Step(s)" list the code number of the previous step(s) that must have been accomplished before this step can possibly be performed, according to the operational procedures.

4. Under "Alternate Step(s)" indicate whether or not an alternate approach may be taken to arrive at the output state.

5. Describe the man/machine operation clearly and completely under "Activity Description."

6. Under "Output State" describe all measurably altered features of the system resulting from the prior activity.

Example of Step 2

Referring to the carlier example presented to illustrate Step 1, we will look only at Function B, "Supply Power to Equipment," in Figure 8.

F. Procedures for Constructing the GSSM

1. Introduction

A major consideration in developing a graphic representation of a system is organization of the model. For even relatively small systems a GSSM is likely to be tightly packed with symbols and verbal descriptions of PEF Units and states. Construction problems can be considerably reduced if major states of the system define transitional segments (e.g., Functions) which are diagrammed separately on clearly identified chart boards. Even so, as chart boards accumulate, it will probably be necessary to make repeated revisions and additions throughout until each segment is well organized and accurately modeled on its respective chart board.

It is assumed that the analyst's goal is to construct the GSSM at the elemental level. If the procedures were follwed in Section E, the completed GMDF would contain a major portion of the information needed

Graphic Model Data Form

Function B. Supply Power to Equipment

Probability P Time T

PEF Unit No.	Prior Necessary Step(s)	Alter-nate Step(s)	Activity Description [2]	Output State	Imposed Requirements P	Imposed Requirements T
B. 1	(Last step of Function A)	No [1]	Throw toggle switch TS on power supply PS_1 to ON position and note that AC ON lamp is lit.	PS_1 is in warm-up condition		
B. 2	"	"	Throw toggle switch TS_1 on power supply PS_2 to ON position and note that AC ON lamp is lit.	PS_2 is in warm-up condition		
B. 3	"	"	Throw toggle switch TS_1 on equipment G_1 [3] to ON position and note that ON lamp is lit.	G_1 is operative		
B. 4	"	"	Throw toggle switch TS_2 on equipment G_2 to ON position and note that ON lamp is lit.	G_2 is operative		
B. 5	"	"	Same, except switch TS_3 on G_3.	G_3 is operative		
B. 6	"	"	Push button B_1 on equipment G_4 and note that ON lamp is lit.	G_4 is operative		
B. 7	B. 1 B. 2	"	(Three minutes after B. 1 & B. 2) throw toggle switch TS_2 on power supply PS_1 to ON position and note that DC ON lamp is lit.	PS_1 is operative		
B. 8	B. 1 B. 2	"	Same, except switch TS_2 on PS_2.	PS_2 is operative		
B. 9	B. 3 B. 4 B. 5 B. 6 B. 7 B. 8	"	Throw toggle switch TS_1 on X to ON position and note that ON lamp is lit.	X is operative		

[1] While alternate approaches may be possible, if the procedures do not indicate that fact, none are listed; they will need to be included in the GSSM, however.

[2] All activities at the elemental level should correspond with those contained in LAMA in terms of level of specificity and verbal description.

[3] G_1 and G_2 may be such gear as VTVM and audio oscillator needed for the checkout of X.

Figure 8. Example GMDF of a Function showing elemental PEF Units.

for such construction. Moreover, since Functions and their resulting states -- as well as most of the states arising from elements -- would have been described, the analyst would be able to make a good estimate as to the amount of material that will be included on a single chart.

2. Construction Rules

Independent of the level of specificity at which the GSSM is constructed -- whether it be at the functional, elemental or some intermediate level -- the unit of construction is the Personnel/Equipment Functional Unit, designated by its input and output states. It is unique to the Graphic State Sequence Model (and critical to its construction) that the states of the system play the primary role. When accurately and completely described, the states allow for an objective examination of all reasonable means by which the transition can be made between the input and output states of a given PEF Unit. Associated with those state/activity units of construction are basic rules for ensuring accuracy and completeness of the model. To apply those rules is the primary task of the analyst; since the same rules must be used repeatedly for each and every PEF Unit, they must become part of the analyst's basic vocabulary. To best achieve firm familiarity, the rules may be worded in the form of questions which are to be asked as each system state is described and as each transitional PEF Unit is drawn and identified.

Figure 9 will be used as a general model of any single PEF Unit (e.g., Function or element). It will be noted that y is the output state resulting from one or more previous PEF Unit transitions and z is all or part of the input state for one or more subsequent PEF Units. As a result, rules applied to y ultimately also apply to z, or vice versa. Whether to focus on y or on z will depend upon whether the analyst begins GSSM construction from the system input state and moves forward (operationally), or whether he starts at the system output state and works toward the input state.

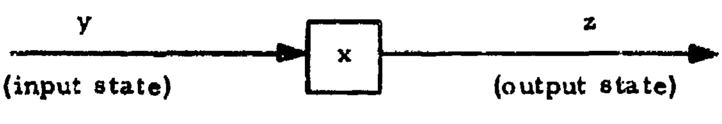


Figure 9. A PEF Unit.

Each identifiable state of the system suggests a multitude of questions leading to the discovery of more detailed requirements. As the

analyst acquires more and more information regarding system requirements and imposed constraints, a larger number of states will be identifiable. Finally, the analyst's perceptive abilities will be called upon to discern the many ways in which the transition can be made from one state to the next. If the system already exists, a primary question will be,"Is the activity in the procedures manual the only way the system can change to the next state?" If the answer is "No," then the alternative possibilities may impose a threat (or greater effectiveness) to achieving the system's mission, if they are discovered by an experienced operator. If the system is being designed, the analyst's knowledge and creative talents will lead him to uncover a multitude of means for making the transitions between clearly defined states.

The freedom with which x and its alternatives can be identified, therefore, will depend initially upon whether or not the analyzed system already exists. Later, it will be seen that in either case, x need not be defined at all until one or more methods or procedures have been determined (or designed) for making the transition from input to output state. Note, therefore, that the first several questions listed below imply rules for describing system states; the nature of x should not impose itself on GSSM construction until all known system criteria have been laid down in the form of system states. The most effective analyst will successfully ignore existing procedural concepts and specify only system requirements until it becomes necessary to indicate the most elemental means for making transitions. At that point, the procedurally specified operation will be exposed as (1) the only reasonable procedure, (2) inappropriate, inadequate or inefficient; or (3) one of several alternatives of which the system is capable. The resulting GSSM will reflect the discovery, and subsequent analysis can then lead to allocation of standards which are consistent with the real model of the system -- not affected by existing procedures which may be based upon desired system functioning.

In order to achieve the best results, therefore, GSSM construction should be undertaken with step-by-step consideration of the following series of questions; the answer to every question must be "Yes" for the diagram to be complete and accurate.

a. Is z (or y, if starting at output) necessary for the system to meet its mission objectives? (If not, it may need to be re-evaluated and either reworded or omitted.)

b. Is z (or y) stated as completely and objectively as possible based on the analysis of performance requirements? (i.e., does the state include the

specified criteria for successful accomplishment? States must be worded so as to be fully described; all relevant features must be included as observable or measurable system conditions.)[1]

c. Does z necessarily follow after y? Or, does y necessarily occur before z? (The GSSM must show the states in the actual relation possible between one another, not necessarily according to the order listed in a procedures manual.)

d. Does z describe only all relevant system features changed since the occurrence of y? (z should be complete without excessive additions.)

e. Does y describe or imply[2] all relevant system features changed to produce z? (The input state to a PEF Unit should include or imply the system conditions which are changed by the PEF Unit activity.)

After all possible system requirements information is obtained and y and z are described in terms of criteria for successful system functioning, then define one or more activities which will produce the necessary transition. Each activity is defined as x.

f. Is y completely adequate for x to occur? (If additional input conditions are needed, those must be included.)

g. Is y just sufficient? That is, does the occurrence of x require the existence of the <u>entire</u> state described by y? (If not, only the essential features should appear.)

h. Does the diagram illustrate all significant occurrences to which y may give rise? In other words, are all operations resulting from y shown?

i. If x is not the only significant operation that might lie between y and z, for this particular system, are the alternatives also included? (If not, they should be.)

---

[1] A state specifies a required system condition; it is not a statement that an activity is completed or that a condition has been altered.

[2] The input state to any PEF Unit includes (1) the changes resulting from the previous transition and (2) features of all previous states which have not been changed during the just preceding PEF Unit.

j. Are alternative operations significant and meaningful? (Alternative activities are almost always possible; therefore, it is necessary to include only those which might reasonably be expected to occur sometimes and omit those which are highly unlikely to occur at all.)

k. Does z fully express the total change in the system resulting from x and only x? (All relevant features of the system state following x, and to which x has contributed, should be included.)

l. Is z complete; that is, does it specify the alternative outcomes of x? (The diagram should show all significant, possible states of the system which might result from x.)

Figure 10 illustrates how the above questions lead to correct GSSM construction.

3. Applying the Construction Rules

To develop an elemental GSSM, one proceeds from the GSSM for the entire system (see example in Figure 11). The first major construction will be at the Function level, and from there through intermediate levels -- if necessary, depending primarily upon the complexity of the system -- down to the most detailed elemental level. At every level of GSSM specificity, however, the above rules should be applied each time a rectangle or line is drawn.

4. Constructing the System GSSM

Step 1

Draw the total system GSSM as a single rectangle with one ingoing (left) and one outgoing (right) line; briefly specify the overall system operation; or system title, inside the rectangle.

Step 2

On the right-hand line, describe the total output state (i.e., the criteria for successful mission accomplishment), and indicate system effectiveness requirements.

Step 3

On the left-hand line, describe the input state of the system (i.e., the state necessary for the system to initiate its mission). The

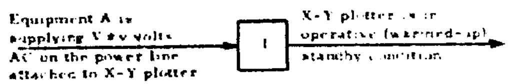
PRINCIPLE

a. A state which is traversed in the GSSM must be necessary to system performance.

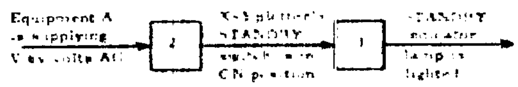
EXPLANATION OF EXAMPLE

The system requires X-Y plotter recordings. The plotter is constrained to be in standby condition before use. To utilize the plotter, an active supply (equipment C) must be appropriately connected to it.

CORRECT



INCORRECT



The X-Y plotter's STANDBY switch must be in ON position for the plotter to be in standby operation. However, the plotter can be in standby operation if the indicator lamp is not lighted. Thus, the state regarding the illumination of the lamp is not necessary and should not be included in the GSSM. Also, the relevant output state is the condition of the system (plotter), rather than the condition of switches or lamps.

Possible PEF Units:
1. Adjust X-Y plotter STANDBY switch to ON and observe indicator lamp is lighted.
2. Adjust X-Y plotter STANDBY switch to ON.
3. Observe indicator lamp is lighted.

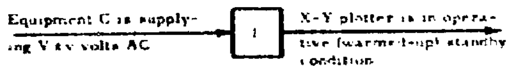
PRINCIPLE

b. The state must be complete and worded to represent an observable, measurable condition of the system.

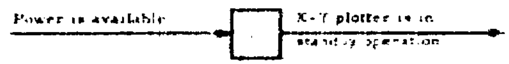
EXPLANATION OF EXAMPLE

The system requires X-Y plotter recordings. The plotter is constrained to be in standby condition before use. To utilize the plotter, an active supply (equipment C) must be appropriately connected to it.

CORRECT



INCORRECT



The X-Y plotter requires specific reference voltages from a specific power source. These must be stated if known and required.

Possible PEF Units: 1. Adjust X-Y plotter STANDBY switch to ON and observe indicator lamp is lighted.

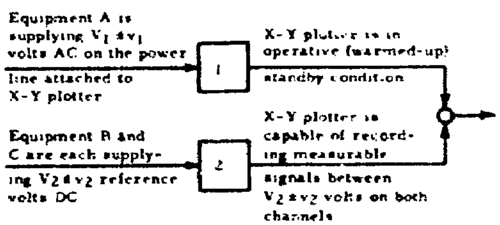
PRINCIPLE

c. Each state must be in the required relation with adjacent states.

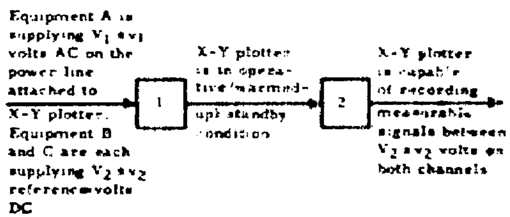
EXPLANATION OF EXAMPLE

X-Y plotter is being prepared for subsequent reception of input signals.

CORRECT



INCORRECT



Supplying power and reference voltages may be performed in any order prior to activating the X-Y plotter to record signals, or both operations may be performed simultaneously.

Possible PEF Units
1. Adjust X-Y plotter STANDBY switch to ON and observe indicator lamp is lighted.
2. Connect jumpers from jacks J_1 and J_2 to plugs P_1 and P_2, respectively, on X-Y plotter.

FIGURE 10. EXAMPLES ILLUSTRATING APPLICATION OF GSSM CONSTRUCTION RULES.

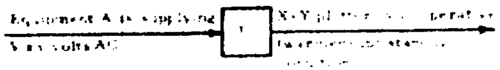
PRINCIPLE

d. The output state should reflect completely only the change that has occurred in the input state.

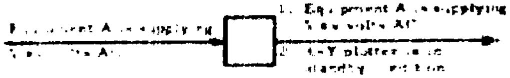
EXPLANATION OF EXAMPLE

The system requires X-Y plotter recordings. The plotter is constrained to be in standby condition before use. To utilize the plotter, an activity supply (equipment A) must be appropriately connected to it.

CORRECT



INCORRECT



Equipment A must be operative before the X-Y plotter can be placed in a standby condition. Thus, item 1 of the incorrect version of the output state is implicit in item 2. Also, it is not clear that the plotter is sufficiently warmed to enable accurate signal recording.

Possible PEF Units: 1. Adjust X-Y plotter STANDBY switch to ON and observe indicator lamp is lighted.

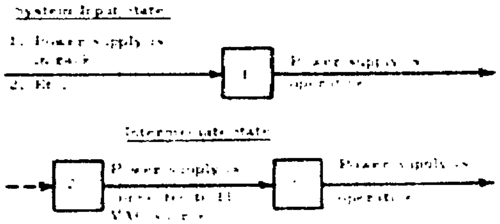
PRINCIPLE

e. The input state must describe completely all relevant features which are to be changed to a succeeding state.

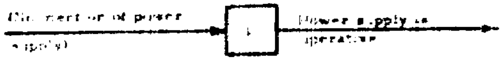
EXPLANATION OF EXAMPLE

Power supply is placed into operation by throwing its power switch to ON.

CORRECT



INCORRECT



In the case where an input state is the system input state, all relevant features should be explicitly described. For many intermediate states, however, certain features are implied, having been described in previous states. In the power example, "power supply is in position" would have been stated previously and need not be repeated.

Possible PEF Units: 1. This PEF Unit covers all required steps and activities between the system input state and "power supply is operative."

2. Connect AC line from power supply to active 115 VAC source.

3. Adjust power switch to ON and observe indicator lamp is lighted.

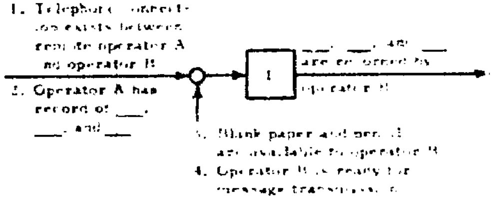
PRINCIPLE

f. The input state must be completely adequate

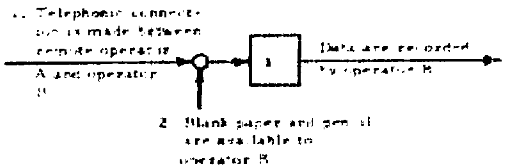
EXPLANATION OF EXAMPLE

Operator A calls operator B on the telephone to relay information. (For example, complete information may consist of amount of fuel available, steam pressure, and instantaneous rate of fuel consumption.)

CORRECT



INCORRECT



Data cannot be verbally transmitted, received and recorded unless receiving and transmitting operators are both prepared and available to one another. Also, the kinds of data should be specified whenever possible. The terms used to describe the kinds of data should be at a level of specificity which causes them to be applicable and meaningful for every operation of a given system. In a radar system, for example, operator B may always receive range, bearing and altitude information, but the range (3 miles), bearing (270°), and altitude (4,000 feet) specific values are not included in the CHSE when the system requires different values of range, bearing and altitude. Specific values are included, however, when they are the only values ever required by the system.

Possible PEF Units: 1. Transmit information verbally via telephone.

FIGURE 10. (CONTINUED)

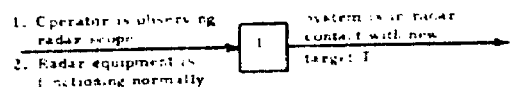
PRINCIPLE

g. The input state must not be excessive for the transition to a subsequent state.

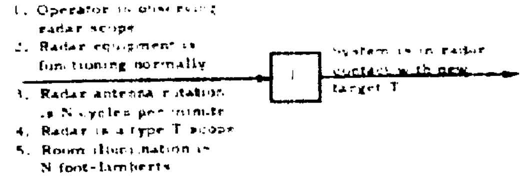
EXPLANATION OF EXAMPLE

A radar operator is in "search" mode until a target is detected, after which it is usually tracked.

CORRECT



INCORRECT



Specifications of equipment capability and environmental characteristics, such as illumination, temperature, etc., should not appear in a model of man/machine operations.

Possible PEF Units: 1. Detect blip and mark blip location on scope with grease pencil.

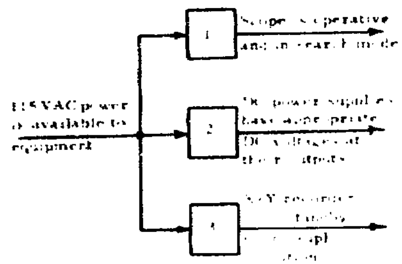
PRINCIPLE

h. Include all significant transitional operations for which a given state is both necessary and sufficient.

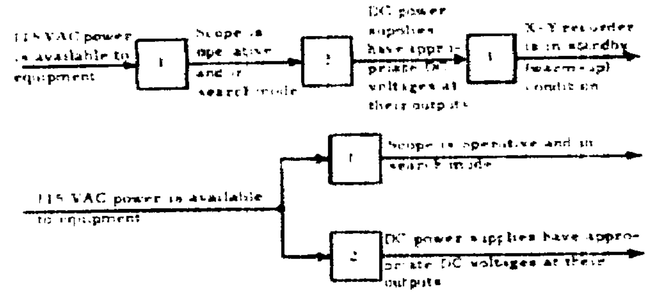
EXPLANATION OF EXAMPLE

Several pieces of equipment have been plugged into a 115 VAC supply which is active.

CORRECT



INCORRECT



It is only necessary to have 115 VAC to turn on the above equipment, and even if the X-Y recorder is not to be used as soon as the scope, once they are plugged into the active 115 VAC source, they can be switched on.

Possible PEF Units
1. Turn on scope. Radar scope automatically goes into search mode when first turned on.
2. Turn on DC power supplies.
3. Turn X-Y recorder to standby.

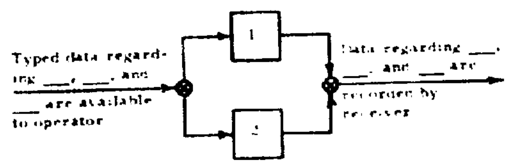
PRINCIPLE

i. Alternative occurrences which could lie between the required input and output states must be included.

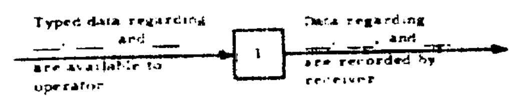
EXPLANATION OF EXAMPLE

Three bits of information are to be transmitted by an operator to a receiver who is located within the same facility as the operator. For example, an officer (receiver) may need to know name of ship, time of arrival, and cargo.

CORRECT



INCORRECT



Although standard operating procedures may specify that data be transmitted from operator to receiver by telephone, if the system permits the message to be hand-carried, and it is likely that it sometimes will be delivered, that alternative must be included.

Possible PEF Units
1. Make telephone connection and read data into telephone.
2. Relay message via mobile courier.

FIGURE 10. (CONTINUED)

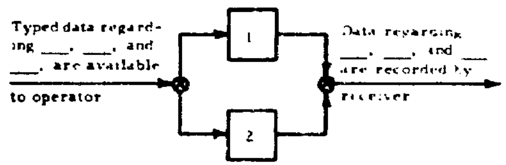
PRINCIPLE

j. Alternative operations by which a desired state may be reached must be meaningful.

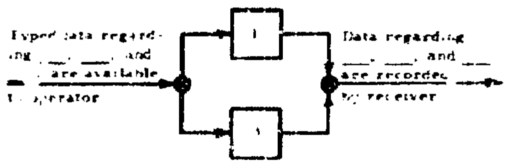
EXPLANATION OF EXAMPLE

Three bits of information are to be transmitted by an operator to a receiver who is located within the same facility as the operator. For example, an officer (receiver) may need to know name of ship, time of arrival and cargo.

CORRECT



INCORRECT



It may be critical to analysis of existing systems, (and it is particularly important in creating new designs) to perceive the many possible -- and sometimes unusual -- ways of making the transition from one state to another. If the system concept precludes or makes highly unlikely the use of a particular transition method, that method should not be included in the GSSM

Possible PEF Units:

1. Make telephone connection and read data into telephone.
2. Send recorded data via courier.
3. Send recorded data via carrier pigeon.

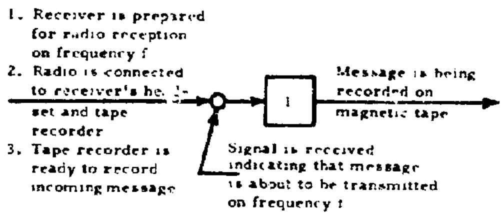
PRINCIPLE

k. The output state must fully express the relevant changes in the system resulting from the PEF Unit.

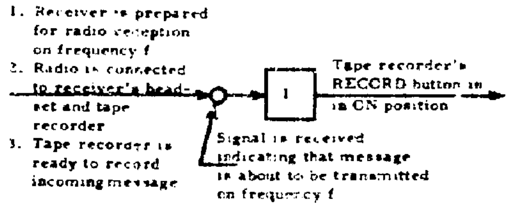
EXPLANATION OF EXAMPLE

Radio operator records an incoming radio message on magnetic tape.

CORRECT



INCORRECT



Although the activity implied by X is "push (record) button," the relevant output state is not the position of the button, but rather that the message is in the process of being stored on tape.

Possible PEF Units: 1. Push tape recorder RECORD ON button and observe RECORD lamp is lighted.

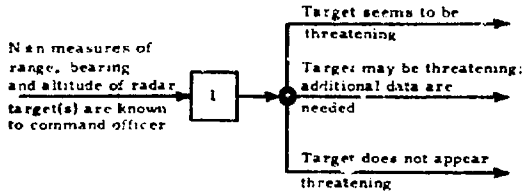
PRINCIPLE

l. All meaningful alternative output states must be specified.

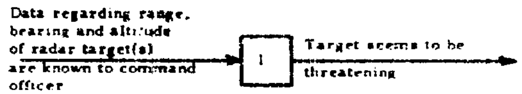
EXPLANATION OF EXAMPLE

Based on the available radar target information, the command officer must make an action decision.

CORRECT



INCORRECT



Several outcomes may result from target data. No decision can be made until a minimum amount of data are known to the command officer (N - n); with sufficient information, however, the command officer must make an appropriate determination based on his knowledge and training. The system must be capable of detecting non-threatening targets and taking no counter action as effectively as it can detect threatening targets and make a defensive move.

Possible PEF Units: 1. Command officer estimates nature of target and decides on appropriate action.

FIGURE 10. (CONTINUED)

CONSTRAINTS

1. Temperature = $T \pm T'$
2. Noise level = $N \pm N'$
3. Illumination level = $I \pm I'$
4. Checkout table is nonconductor
5. Operator stands on rubber mat

INPUT STATE

1. X is located at L_x
2. Checkout gear, G_1, G_2, G_3, and G_4 are located at L_1, L_2, L_3 and L_4, respectively
3. L_x, L_1, L_2, L_3, and L_4 are accessible to operator
4. Operator is ready to checkout X and has appropriate procedural instructions

→ **Bench Checkout of X** →

OUTPUT STATE

1. Measurements, m, meet criteria, M, within tolerance, a; i.e.,
   $m_1 = M_1 \pm a_1$
   $m_2 = M_2 \pm a_2$
   $m_3 = M_3 \pm a_3$
   etc.
2. X is located at L_y (ready for installation)

Figure 11. GSSM of the hypothetical system.

accuracy of the input state description can be checked as more detailed models are constructed, since every change in the state of the system must procede from a prior state which has been explicitly described. Thus the input state sets the complete stage for all subsequent state changes.

Step 4

Above the rectangle, list all constraints placed by designers on the system's operation.

5. Constructing the GSSM at the Function Level

The Function GSSM is the primary basis for organizing more detailed models and is essential to the accurate mapping of the system in greater detail. The first steps in its construction require very little additional data from that used to construct the System GSSM; however, it requires considerable thought and understanding of the system's mission to properly describe Functions and states to which they give rise.

Modeling existing systems differs somewhat from modeling for design. If a system already exists, some definite assumptions can be made regarding constraints on equipment and manpower available. For design, only gross descriptions of Function-determined states can be made. Also, in designing a new system, the analyst will usually begin with the output state of the system and develop the model "backwards" toward the input state (which will often not be entirely specifiable until the design is completed). Designed systems may be modeled from input state to output state, from output state to input state, or from both ends toward the middle. Therefore, a certain amount of flexibility is possible in applying the following steps.

Step 5

Using the basic construction rule questions as a guide, define the major system states, which are the requirements for mission accomplishment; describe the states between each rectangle comprehensively, but without being too specific; that is, indicate all requirements but without including any precise numerical values. If desired, a general name for the Function may be written inside the rectangle.

Function titles are relatively unimportant, as long as they indicate the general activity involved in going from input to output state. It is particularly important to develop the habit of specifying between-function states of the system before labelling functions, since those

states aid in defining the required operation. The purpose of Step 5 is to organize the modeling procedure rapidly by spending minimal time collecting specific data. Care should be taken, however, to include all important functions in appropriate relation to one another. The result should be a rough but accurate model which could apply to any system having the same mission. (See Figure 12.)

Step 6

Revise between-function states to include all specific, measurable characteristics that are obtainable. (System requirements or objective criteria of successful performance.)

Example

Referring to the sample GMDF of II. E, the GSSM would initially appear as shown in Figure 13, with system states clearly defined. Note that the functions -- not the states -- could apply to the checkout of any piece of electrically powered equipment.

Assume that some of the checkout of X must occur before power is supplied to the equipment; some of the checkout can occur before or after power is supplied. In that event, Functions B and C are not clearly separable as indicated in Figure 13. At the Function level, however, Figure 13 is still acceptable because it is primarily descriptive; a more specific diagram would no longer be system independent. Thus, a second breakdown may be performed to incorporate the new information. Figure 14 illustrates how that would be done.

6. Constructing the GSSM at Intermediate Levels

Figure 14 illustrates a form of intermediate level GSSM. More commonly, the procedure for producing intermediate models is to follow Steps 5 and 6 for each Function separately. However, it is quite possible to find that some functions fall readily into elements, while other functions in the same system may require one or more intermediate level models to perceive and map the system correctly.

It will be noted that the final output state of the intermediate level GSSM must be identical to the output state of the corresponding function. However, it should be remembered that part of the GSSM output state includes the unchanged states occurring anywhere within the prior portions of the GSSM.

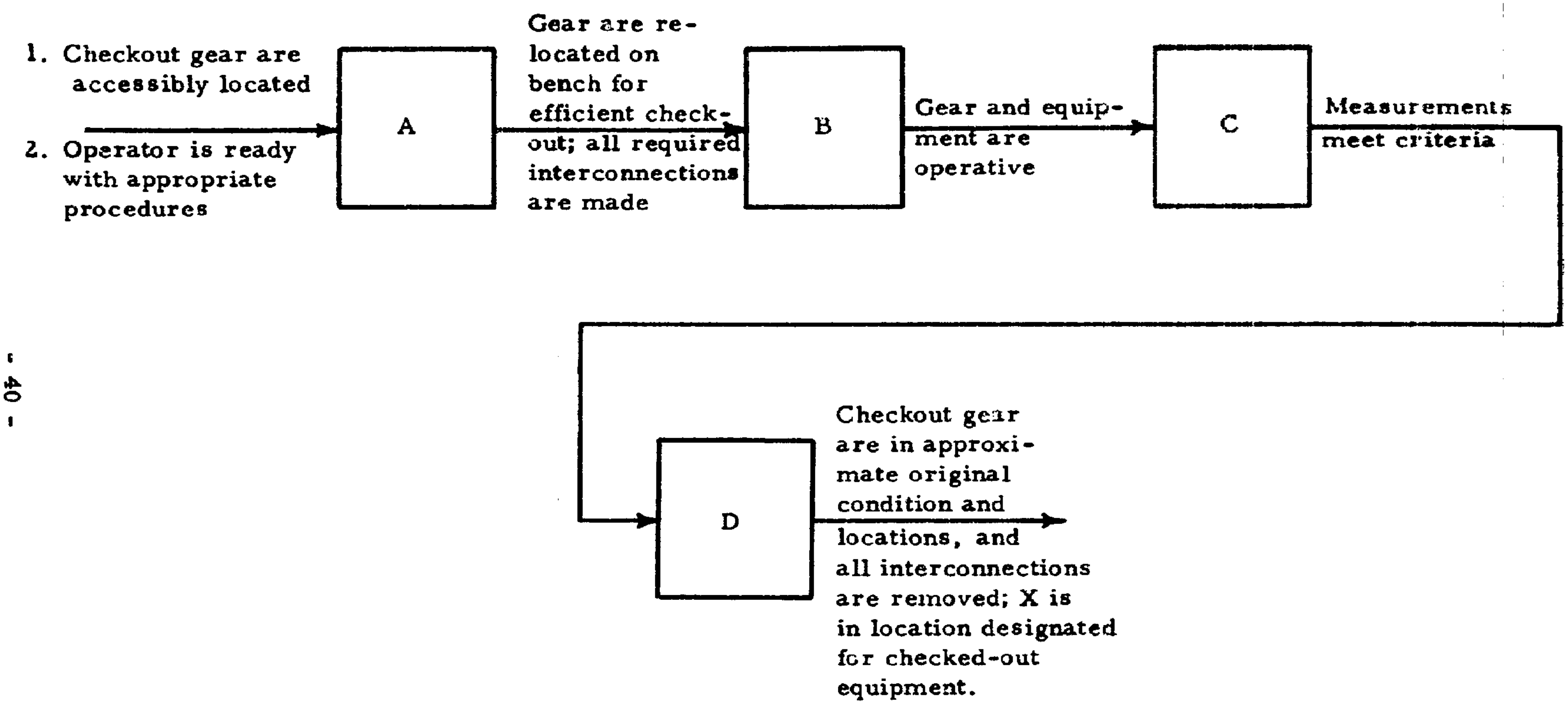


Figure 12. Rough model of the Functions of the hypothetical system (Step 5).

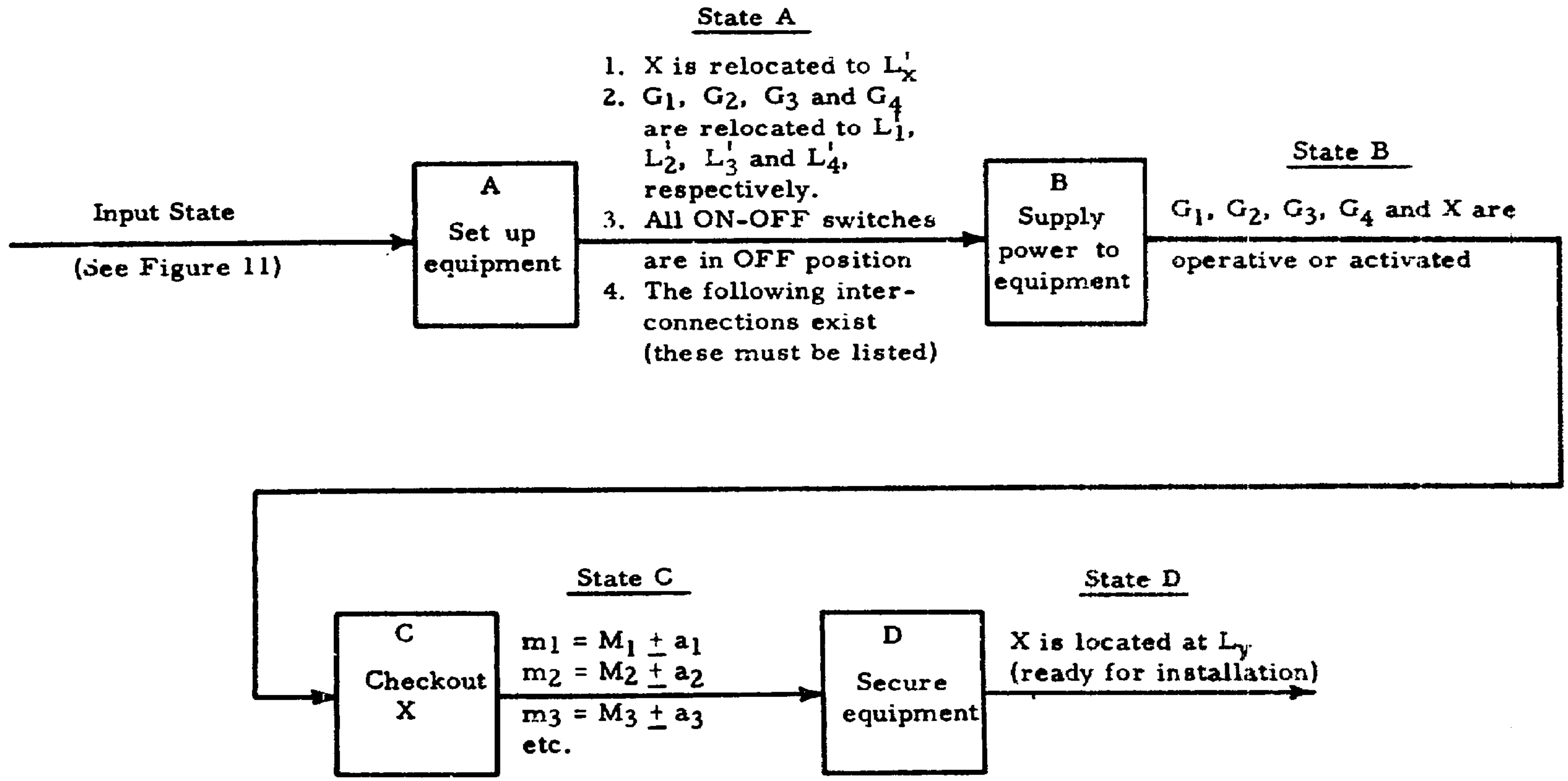


Figure 13. GSSM of the Functions of the hypothetical system (Step 6).

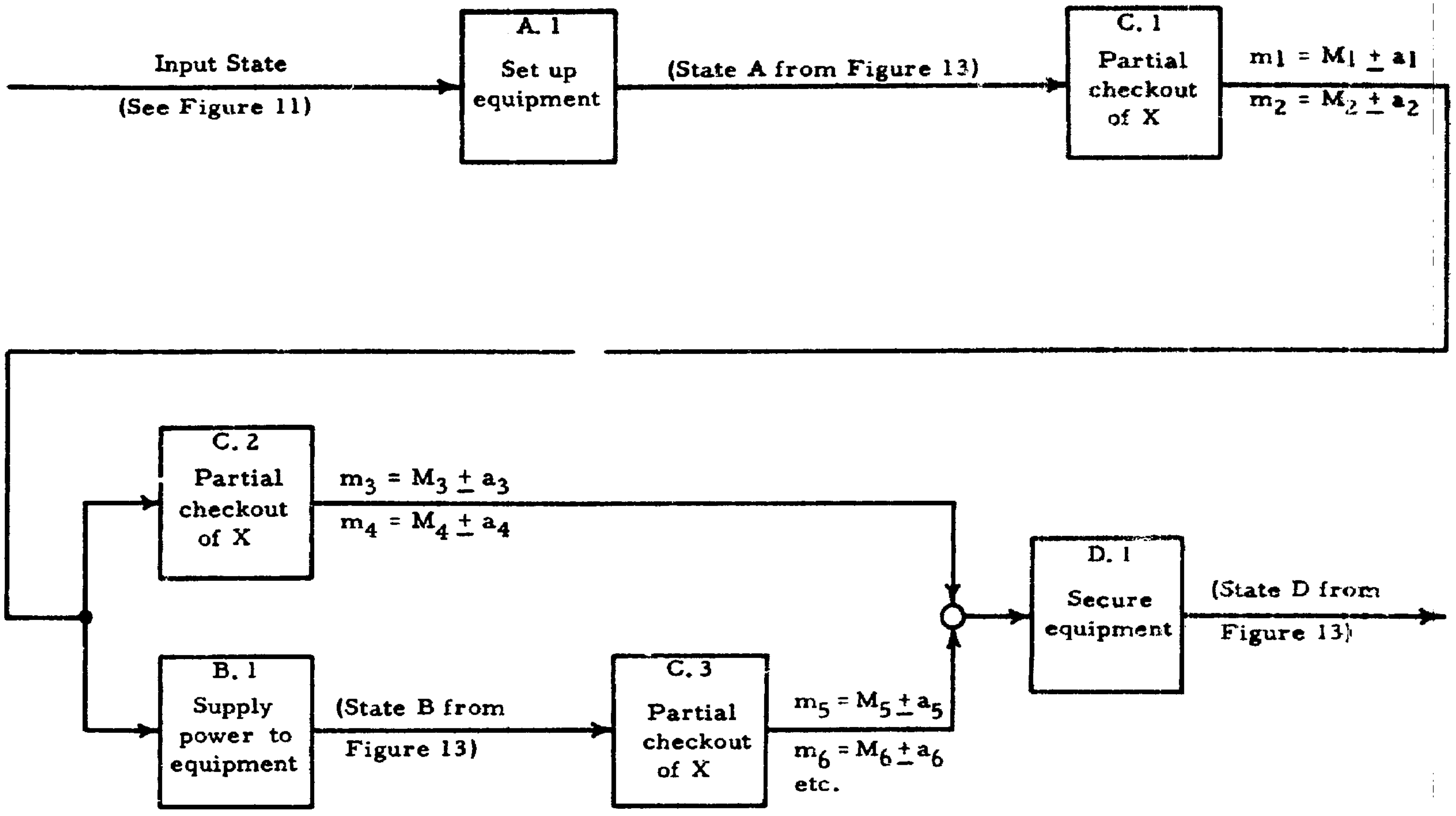


Figure 14. Example of a possible second level GSSM (from Figure 13).

7. Constructing the GSSM at the Element Level

The procedures for constructing models at the element and intermediate levels are identical in that Steps 5 and 6 are followed, unless sufficient immediate knowledge exists to apply 6 directly. It is understood that the construction rules are always applied.

Function and intermediate level models provide the organization and system states for constructing the GSSM at the element level. Each PEF Unit in the most recently made model can be treated as if it were an autonomous operation. That is, for example, if all states have been clearly defined between Functions, then an elemental model of the states within each Function can be developed to take the system from that Function's input state to its output state, and that can be done relatively independently from the diagramming of other Functions. By having system states carefully and completely specified, it will always be clear exactly what portion of the system's operation is under analysis.

Referring to the example in Figure 13, the GSSM would be constructed as shown in Figure 15. In order to conserve space, note that the code numbers in the boxes of the diagram refer to the "Activity Descriptions" in the example of Figure 8.

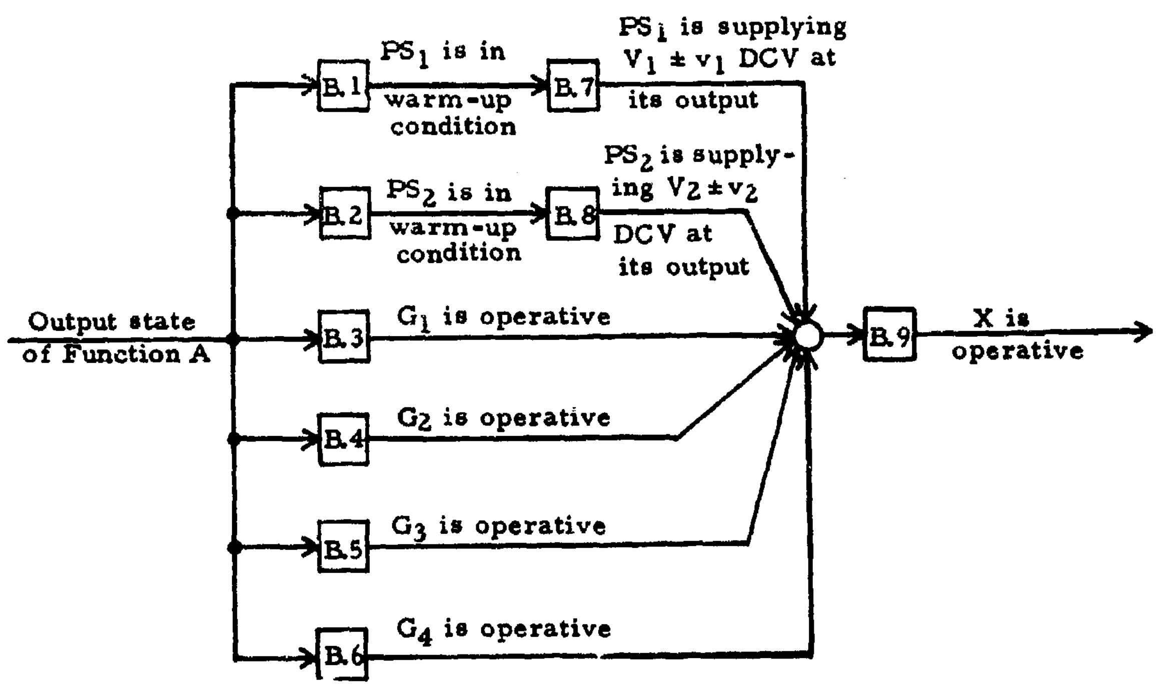


Figure 15. GSSM of Function B in example.

The features to be observed in the examples are the following:

1) The output states of B. 1, B. 2, B. 3, B. 4, B. 5 and B. 6 may be produced in any sequential order, or simultaneously by different persons.

Assume that the GSSM constructor examines that data and finds no clearly specified requirement that B. 9 depends on the simultaneous existence of all the prior states (produced by B. 3 through B. 8) shown in Figure 15, even though the procedures specify that sequence; as a result, he consults one of the engineers and discovers that B. 9 can occur when V_1 and V_2 exist at the outputs of PS_1 and PS_2 respectively, and when G_4 is operative, but B. 9 does not require that G_1, G_2 and G_3 be operative. The GSSM for Function B would then be revised to appear as shown in Figure 16.

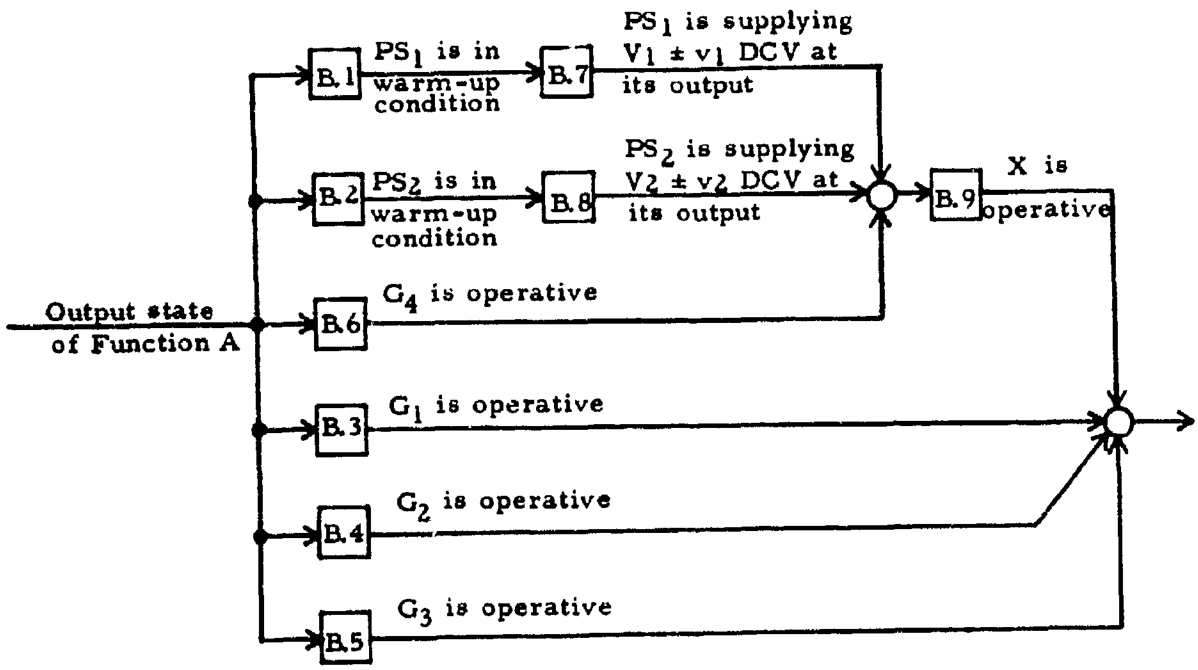


Figure 16. A revision of Figure 15.

2) The system requires that the equipment be operative; it does not require simply that lamps light. Indicator lamps serve as feedback mechanisms, but their illumination does not in itself represent the required aspect of successful system performance.

Even though the system can become operative without the operator's perceiving the indicator lamp, simply observing an indicator lamp should not be shown in the model as an alternative procedure. As a general rule, the GSSM should not contain any set of alternative PEF Units which only differ in degree of feedback information, unless the alternatives can be found in the LAMA matrix. However, PEF Units should describe the entire activity of which the system is capable to make the transformation between input and output states. (For example, use "Turn POWER switch ON, and observe POWER ON lamp illuminates," if that is a means of producing an equipment-operative condition; do not simply indicate, instead, "Turn POWER switch ON.")

3) Tube type power supplies will generally operate if the DC voltage is turned on sooner than the manufacturer recommends, but the load on the supply may be excessive, resulting in a reduction in life expectancy and reliability. However, inoperativeness, for any reason, is a maintenance and maintainability problem and not relevant to the operational model of the system. If the supplies function without warm-up, the output states of B.1 and B.2 are not system requirements (that is, the three minute wait is not essential to successful system performance) and those PEF Units should not appear in the GSSM. On the other hand, if the supplies will not operate without the delay, and if there is a constraint not to use a time delay relay, a new PEF Unit, "Wait at least three minutes" will need to be inserted between the following states: "PS is in warm-up process; DC is inaccessible" and "PS is in warm-up condition; DC is accessible."

4) It is assumed in Figure 15 that X cannot be turned ON unless the output states of B.3 through B.8 all exist. However, investigation may prove that X may be turned on at any time; if that were true, it should be noted that the input state for B.9 would be identical to the input state for B.1 through B.6.

G. Special Constructions

1. Transition-Equivalent Alternatives

Figure 17 indicates that two entirely different operations are possible to make the transition from the input to the required output state; however, it is understood that each operation may be associated with a different probability of arriving at that state.

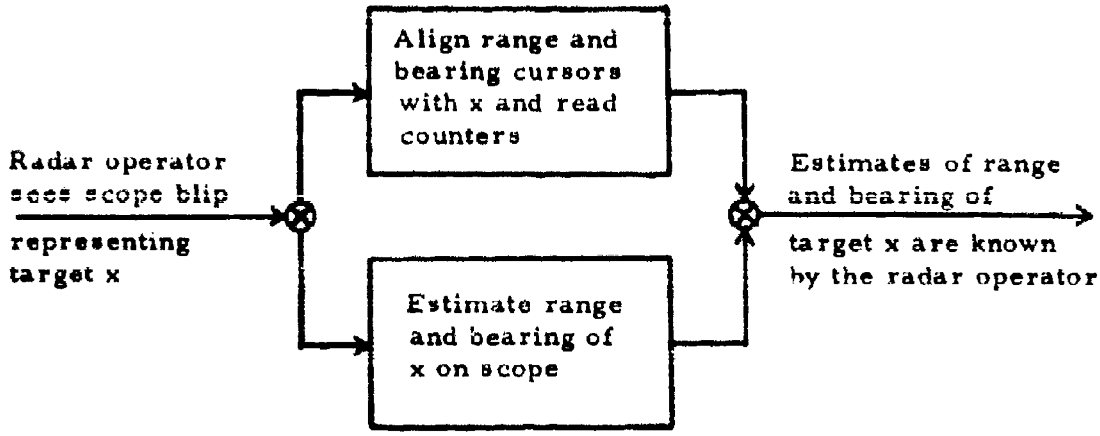


Figure 17. Example of transition-equivalent alternatives.

Figure 17 is an example of transition-equivalent alternatives; one and only one of two or more procedures can occur to make the system required transition from the given input state to the common required output state. If the system inherently makes it possible to achieve the transition in more than one way, all reasonable alternatives must be included in the GSSM. Such alternatives may be contingent on arbitrary choices available to an operator as the result of inherent system capability. That is, the operator may perceive several ways to accomplish a task or the system may allow for different approaches under various assumptions regarding conditions under which operation proceeds.

2. System Required Alternatives

Figure 18 shows an example of alternatives which depend on the (unpredictable) nature of the input state.

The example assumes that all classified messages received by teletype are to be transmitted to a post commander by courier and all unclassified messages are to be transmitted by telephone (due to requirements for safety an. economy, respectively). At any given time, however, it cannot be predicted which type of message will be received by the operator for transmission. The alternatives arising from the different

possible input states are called "system required" because the system has different constraints imposed on it for each possible input state.

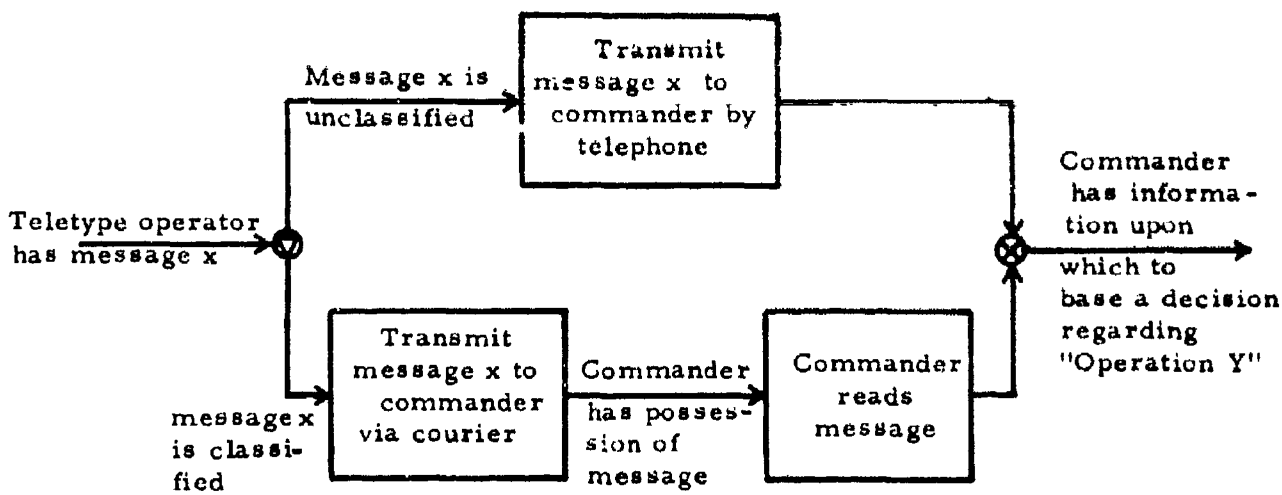


Figure 18. Example of system-required alternatives leading to a common output state.

3. Backup Operations

Complex systems may include requirements which can only be met by performing a set of activities more than once. For example, (1) an individual may be required to perform the same set repeatedly so as to satisfy stringent criteria in the output state, or (2) two or more individuals may perform the same activity either independently or in conjunction with each other, so that the final output state is a function of their joint efforts.

a. [illegible]

When a system requires a set of activities to be repeated one or more times, the output state can be expected to have a higher probability of occurring correctly than if the set were performed only once. (Such repetition will also result in higher allocated probabilities to PEF Units within a cycle.) Figure 19 shows an example of a cyclical repetition in a simple checkout operation of a power supply.

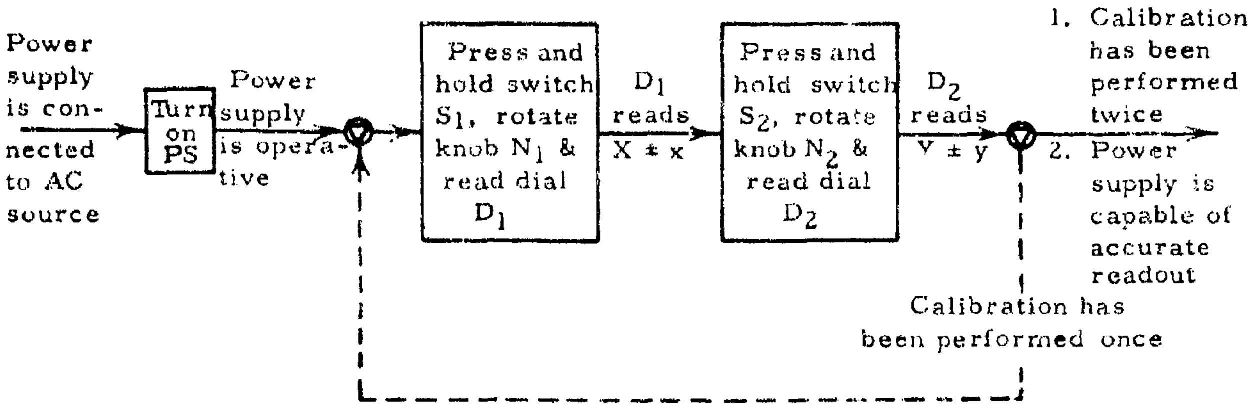


Figure 19. Example of a calibration procedure on a power supply.

When operating procedures (or design criteria) specify this type of repetition, the GSSM should include a dashed line which indicates exactly which state is assumed still to exist and, therefore, which activities are to be repeated. The dashed line should be identified by conditions (system state) which lead to repetition, and the undashed output

ine should indicate the [illegible] existing such that no further repetitions are required. Do not duplicate, triplicate, etc., the same sequence of activities in the GSSM.

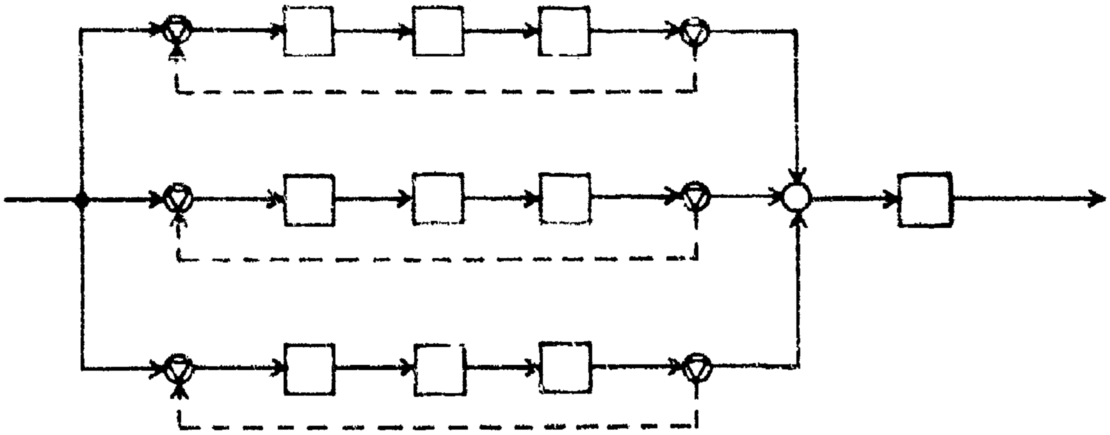
Figure 3 shows a hypothetical radar system in which the radar operator, plotter and watch officer are periodically exchanging target information. Unlike the system described in Figure 19, repetition in this system will usually result in additional information (e.g., direction and velocity of target) rather than increasing the accuracy of the same information. Thus, the output state "Watch officer has sufficient data to make judgment about target's identity" may importantly depend on the number of such repetitions. Whether or not that is the case, however, may depend on the particular system and operating procedures which are assumed to be used. If the target is a high-speed nuclear missile, for example, it may be less appropriate to wait for additional information; in effect, the system which includes defense measures may have a lower probability of being accomplished. The analyst must therefore structure the GSSM according to the unique characteristics and requirements of a given system. Like Figure 19, the repetition cycle in Figure 3 is denoted by a dashed line.

b. <u>Concurrent Duplication</u>

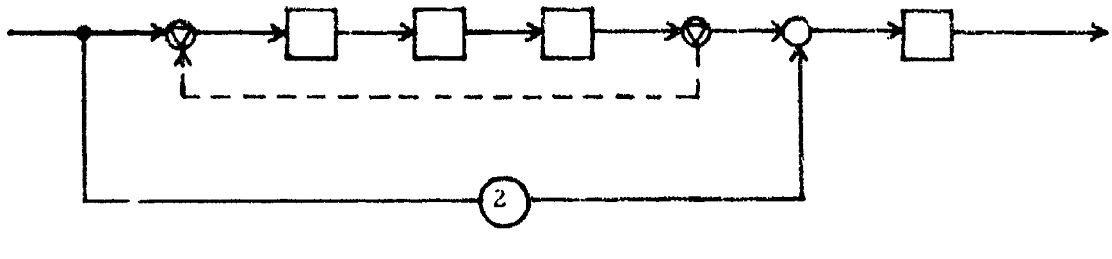
Figure 20 represents the portion of a system in which two or more independent but identical sets of activities are performed simultaneously in order to satisfy a very high SER. The probability that the system successfully achieves its mission is expected to increase with the number of duplications; therefore, this special situation must be represented in the GSSM. Figure 20 illustrates how concurrent duplications are indicated in the GSSM; a line is drawn paralleling the activity or activities which are duplicated. The line is interrupted by a circle within which is a number corresponding to the minimum number of concurrent duplications required by the system. Thus, Figure 20b has the same interpretation as Figure 20a.

c. <u>Redundancies</u>

When concurrent operations provide backup to aid the accuracy of a primary activity through feedback, the situation is said to involve redundancy. Figure 21 illustrates a hypothetical, redundant set of conditions in which the system state resulting from activities A and B are checked for accuracy in C, D and E; the latter provide feedback to increase the likelihood of the correct accomplishment of A and B. Figure 21 also indicates the very likely alternative condition that the system allows for A and B to be performed without <u>feedback</u> from C, D and E.



(a)



(b)

Figure 20. Schematic representation of concurrent duplications (with cyclical repetition).

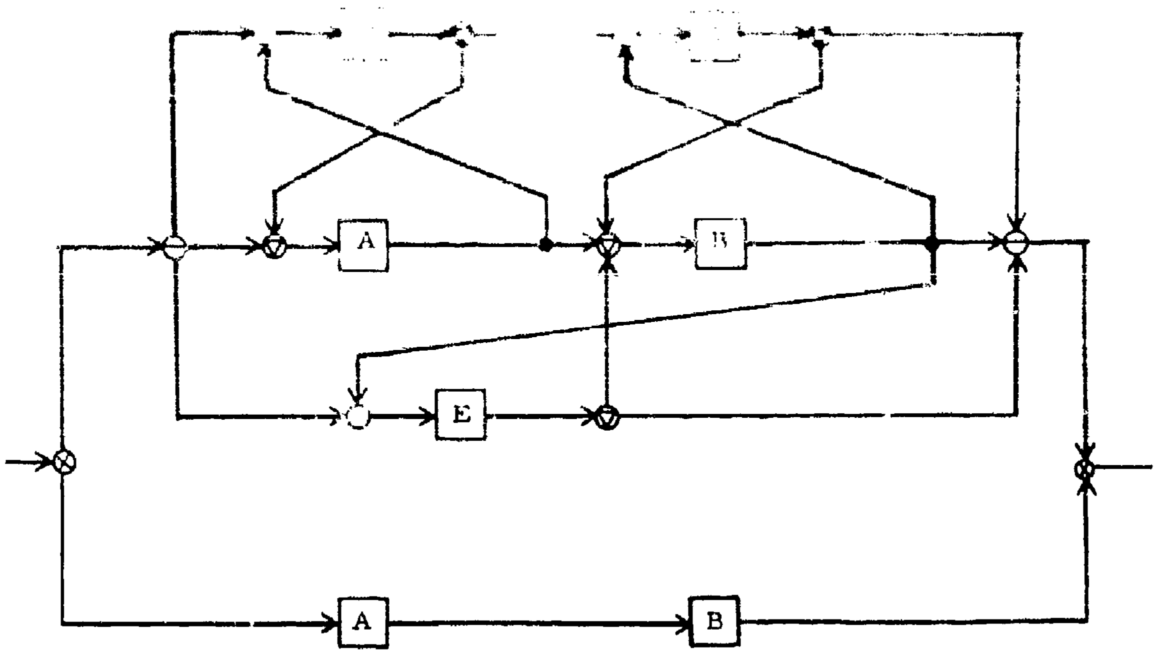


Figure 21. Example of a redundancy.

H. Some Additional Construction Rules

1. Transition-equivalent alternative activities or activity sequences should begin at the common input state and end at the common output state, even if elements must be repeated. For example, assume the system "going home from the airport" defined as shown in Figure 22.

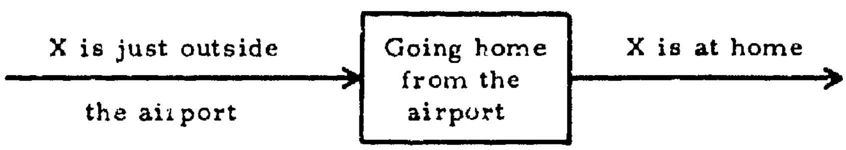
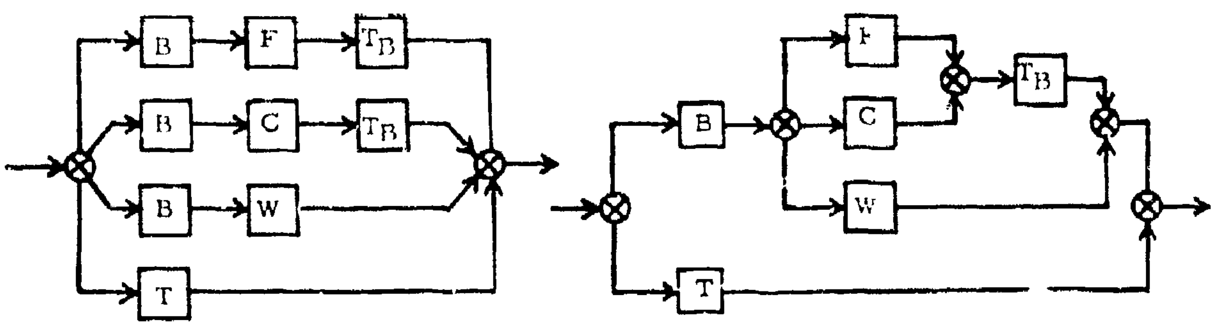


Figure 22. Another hypothetical system.

X may take a bus (B) or hail a taxi (T). If X takes a bus, he may walk home from the bus stop (W) or take a Taxi (T_B). If X chooses to take a taxi from the bus stop, he may be able to find one locally available (F)

[illegible] may need to call for one via the corner telephone (C).[1] (See Figure 23.) By using the correct procedure, one can analyze each total strategy independently.

CORRECT	INCORRECT
The correct procedure is to follow the above rule to start and end at the same common states.	Do not try to minimize the number of blocks in the diagram (even though it presents the same diagrammatic information as the correct version).



(a) (b)

Figure 23. Example of establishing a single set of transition-equivalent alternatives.

[1] Note: Other alternatives are conceivable, but based upon one's knowledge of the system, they are not meaningful. For an absurd example, X might conceivably find a pair of skates and skate home. For a more sane example, X could have driven a car to the bus stop and left it there until his return. However, based on our knowledge of X (or lack of parking spaces near the bus stop) the probability is almost zero that he would use that strategy; perhaps X has never owned a car, he is too young to drive, or his wife always uses the car.

2. Where transition-equivalent alternative activities are not exclusive, establish diagrammatic combinations which force them to be exclusive.

For example, assume that X told his wife (C_W) that he might call her when he arrived at the airport and that he might either call a taxi (C_T) to take him home or ask her to pick him up, depending on his feelings at the moment. Thus, X may call for a taxi or call his wife or both, as shown in Figure 24.

CORRECT	INCORRECT
The correct procedure is to establish exclusive alternatives. This enables independent analysis of all possibilities.	Do not try to improvise an "and/or" symbol.

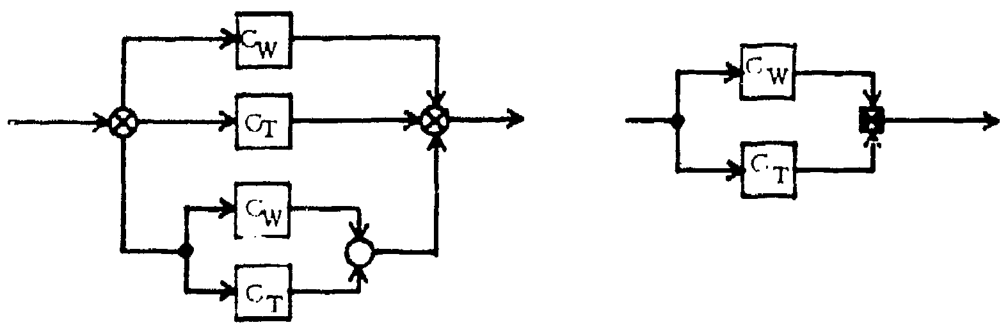


Figure 24. Example of establishing mutually exclusive alternatives.

3. Where alternative activities depend upon other contingencies, those contingencies are summated with the existing state of the system. To illustrate, consider the example under 1 above; assume that if a taxi is available (T') when X gets off the bus, he will take it, otherwise he will walk. This situation is diagrammed in Figures 25a and 25b, which are equivalent alternatives.

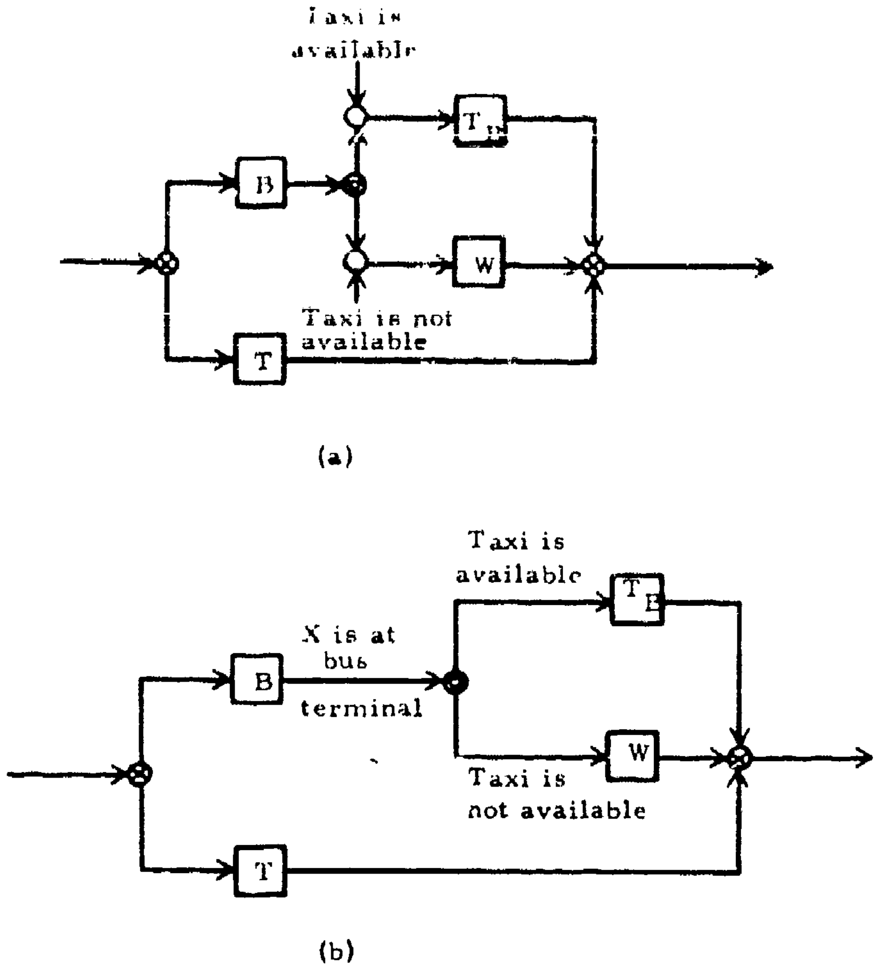


Figure 25. Example illustrating inclusion of contingencies.

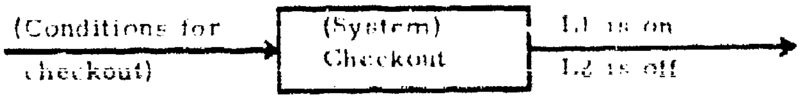
4. Always avoid repeating what is already implicit.[1]

Example 1

Assume an operator has three checkout switches to operate. S1 turns on one light, L1, and S2 turns on L2. Subsequently, S3 turns off L2 and leaves L1 on. Figure 26 illustrates the correct GSSM.

---

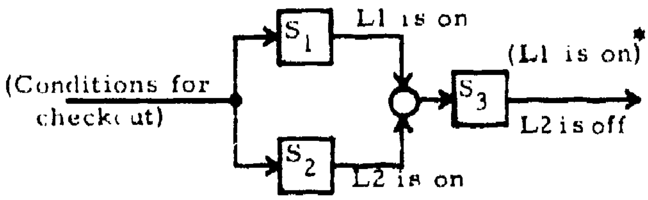
[1] The example which was carried through the previous three rules cannot readily be used to illustrate this rule. Thus, it is to be noted that every rule may not be applicable to all systems; every system must be approached uniquely.



(a)

CORRECT

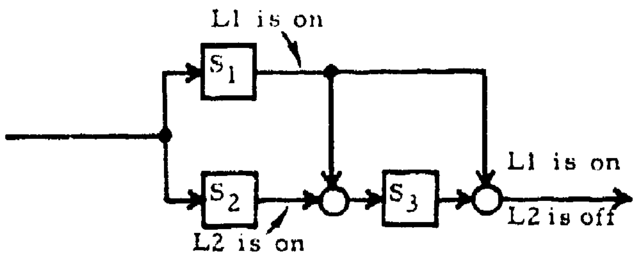
The correct diagram gives all necessary information.



(b)

INCORRECT

Do not indicate a state that is already specified by the diagram.



(c)

Figure 26. Example illustrating an implicit state.

*Parenthetical information is understood from a previous state and would normally not be repeated.

III. CONSTRUCTING THE MATHEMATICAL STATE SEQUENCE MODEL

A. Introduction

The MSSM essentially consists of an equation which expresses the relation between the required probability of achieving the system output state and the probabilities (to be derived) of accomplishing the PEF Units which the system comprises. Although the MSSM involves relations among probability values, it contains all information necessary for allocating performance times as well as probabilities of accomplishment, if time is also included as a system effectiveness requirement. The purpose of the MSSM is to enable the mathematical derivation of performance standards from the SER.

The MSSM is a relatively simple translation of the GSSM; since the graphic model is in the form of a logic-flow diagram, successive states can be conceived as being probabilistically related to one another. For that reason, the MSSM can be no more accurate than the GSSM from which it is directly derived.

If TEPPS computer program is to be employed, it will generally be unnecessary to construct an MSSM, since the computer operates upon symbolic data which directly describes the GSSM. Thus, the computer implicitly constructs the MSSM in the process of operating on those data. Nevertheless, it is important to understand the structure of the MSSM in order to (1) symbolize the GSSM correctly, (2) arrange the data for appropriate computer analysis, and (3) interpret the results of the analysis. In particular, in order to use the computer, it will be essential to understand Steps 1 and 2 in the Procedure part of this section. Instructions for constructing the mathematical model will be presented below. Examples will be used to illustrate each step in the procedure. The few symbols listed in Table II are the MSSM tools and components which enable translation from the GSSM.

Table II

MSSM Symbols

Symbol	Meaning	Example
$P(x)$ or P_x	The probability of whatever is contained in the parentheses.	$P_{B.3}$ = the probability of the required output state of element 3 of Function B. (It is assumed that the input state to B. 3 initiated that elemental personnel/equipment function.)
$\prod_{i=1}^{n}$	The product of the n values following the symbol.	Assuming the system has four Functions, as shown in Figure 13, $\prod_{i=1}^{4} P(i) = \prod_{i=A}^{D} P(i) = P(A)P(B)P(C)P(D)$ That is, the symbol says "multiply" the four probabilities," substituting for i all letters from A to D.
$\sum_{j=1}^{m}$	The sum of the m values following the symbol.	$\sum_{j=1}^{m} X_j = X_1 + X_2 + X_3 + X_4 + X_5$ Just as for the product symbol, the summation symbol says, "substitute for j all whole numbers from 1 to m."

B. Basic Principles

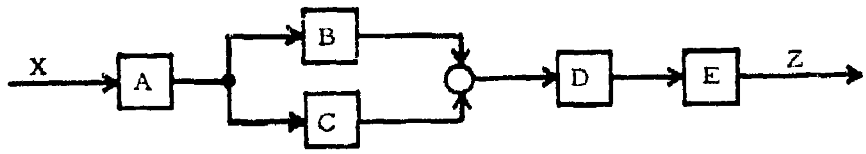
All Mathematical State Sequence Models are expressions relating the probability of an output state to the probabilities of accomplishing the PEF Units giving rise to that output state. Since TEPPS is concerned with the probability of success for each system operation--rather than for an average of many operations--only one rule applies each time:

Rule 1: The probability of the output state of a required set of PEF Units is related to the product of the probabilities associated with those PEF Units.

The mathematical expression of this rule is:

$$P_o = P(in) \prod_{i=1}^{n} P(i)$$

where P_o is the probability of the output state, P(in) is the probability of the input state, and i represents the code numbers assigned to the component PEF Units. An example of the application of Rule 1 is shown in Figure 27.



$$P(Z) = P(X)\,P(A)\,P(B)\,P(C)\,P(D)\,P(E)$$

$$P(Z) = P(X) \prod_{i=A}^{E} P(i)$$

Figure 27. Application of MSSM Rule 1.

Because there often are alternative sets of PEF Units and output states, there may exist many mutually exclusive paths by which to arrive at the system output state from a given input state. Moreover, the different alternatives within a set are likely to be associated with different probabilities. Thus, for every possible path in the GSSM there is a corresponding and identical equation that only differs from the others in that a different set of probabilities are used.

Since only one alternative can be selected for any one system operation, each alternative in a set must contribute to satisfying the SER. To symbolize independence (or mutually exclusive characteristice) of alternative PEF Units, Rule 2 is used.

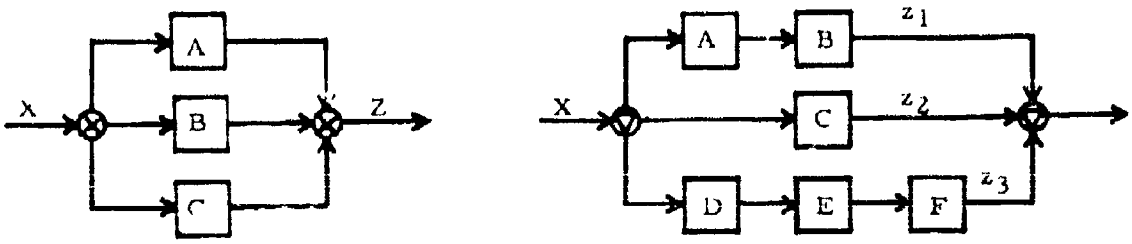
Rule 2: The probability of the common output state of an alternative set of PEF Units is symbolized as the bracketed matrix of the probabilities associated with those PEF Units.

The second rule applies wherever the GSSM has a circle with a cross or triangle. The "common output" state exists where a circle with a cross has two or more arrows entering it from alternative operations which lead to that state. The general mathematical expression for that arrangement is:

$$P(\text{common output}) = P(\text{in}) \; [P_j]_{j=1}^{m}$$

where P(in) is the probability of the common input state for the alternative set implied by the GSSM line leading into the circle with a cross or triangle, and j represents one of the alternatives. Simple examples of the application of Rule 2 are shown in Figure 28.

It may be noted that a set of alternatives may involve several PEF Units which taken together must be symbolized as a product (see Figure 28b). It is of particular importance to note that alternatives represented by circles with crosses have probabilities enclosed within square brackets, in the MSSM, while alternatives designated by circles with triangles have probabilities within parentheses.



$$P(Z) = P(X) \begin{bmatrix} P(A) \\ P(B) \\ P(C) \end{bmatrix}$$

$$P(Z) = P(X) \left[P(j) \right]_{j=A}^{C}$$

$$P(Z) = P(X) \begin{pmatrix} P(A)\ P(B) \\ P(C) \\ P(D)\ P(E)\ P(F) \end{pmatrix}$$

(a) (b)

Figure 28. Applications of MSSM Rule 2.

While the MSSMs for the two kinds of alternative sets appear similar, they represent quite different functional situations. In Figure 28b, for example, the input state, X, may take one of three distinguishable forms, while in Figure 28a, X is the necessary and sufficient condition for A, B, or C to occur. Similarly, states z_1, z_2, and z_3 are equally acceptable output states in Figure 28b, but they are not identical; in Figure 28a, however, all three PEF Units produce the common output state Z. An understanding of these differences between the two types of alternatives will be critical to accurately preparing the data for the computer.

C. Procedure

Generally speaking, it will be necessary to write a separate set of equations for each discernible segment of the GSSM, since most models will be quite complex. To aid in construction, and to provide the coding necessary to use the TEPPS computerized program for deriving standards, it is necessary to assign dummy reference symbols to certain states of the system.

Step 1

Construct a skeletal GSSM from the one being analyzed. The skeletal model is a reduced model, identical to the original but with no verbalizations; only lines, logic symbols, and rectangles containing identification numbers are used. An example is illustrated in Figure 29.

Step 2

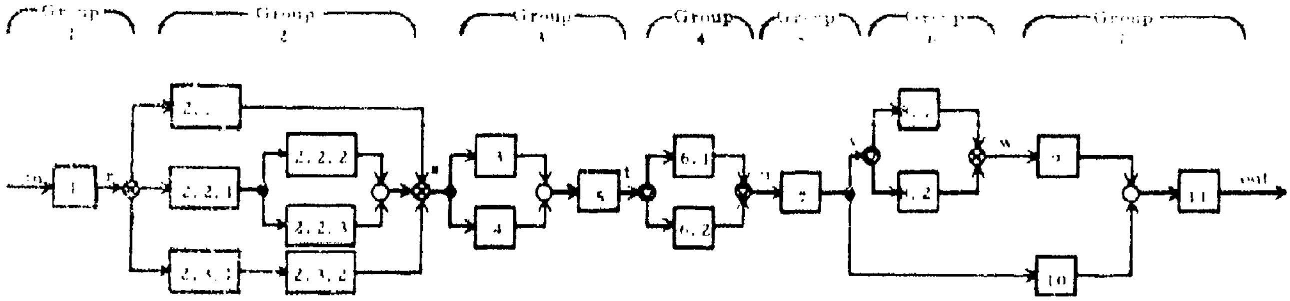
Assign an identification number to each PEF Unit according to the following rules:

a. Assign a digit -- starting with 1 -- successively to each "Set" of PEF Units. A Set is defined as (1) a GSSM element which is not a member of any alternative group (Unit Set), or (2) more than one (Compound Set) which contains elements in a chain, bounded by circles with either a cross or triangle. Branches from a dot (ultimately entering an open circle) are treated the same as if they were along a single, continuous line. Thus, in Figure 29, PEF Units 1, 3, 4, 5, 7, 9, 10, and 11 are all Unit Sets. The remaining GSSM elements are members of one of the three Compound Sets.

b. Assign a second digit -- sta 'ing with 1 -- to every element within each Compound Set. (A Unit Set is always represented by only one digit.) For example, in Figure 29, there are only two members in the Compound Sets whose first digits are 6 and 8.

c. Assign a third digit --starting with 1 -- to every element in a series lying within a Compound Set. In Figure 29, the second group in Set #2 has three series elements. (In the diagram, PEF Units joined by a dot and open circle are treated the same as if they were strung in a sequential chain.)

d. Continue adding extra digits for Compound Sets within Compound Sets. The principle is this: odd digits represent sequential position, and even digits represent parallel (alternative) GSSM position. An example ˊˆ a more complex arrangement is shown in Figure 30, which is ˏ 'esented simply to illustrate another application of these procedures.



1. $P_r = P_{in} P_1 = P_1$

2. $$P_s = P_r \begin{pmatrix} P_{2,1} \\ P_{2,2,1}\, P_{2,2,2}\, P_{2,2,3} \\ P_{2,3,1}\, P_{2,3,2} \end{pmatrix}$$

3. $P_t = P_s P_3 P_4 P_5$

4. $$P_u = P_t \begin{bmatrix} P_{6,1} \\ P_{6,2} \end{bmatrix}$$

5. $P_v = P_u P_7$

6. $$P_w = P_v \left[\begin{matrix} P_{8,1} \\ P_{8,2} \end{matrix}\right)$$

7. $P_{out} = P_o = P_w P_9 P_{10} P_{11}$

To remove the reference numbers, substitutions are made as follows:

$$P_o = P_u P_7 \left[\begin{matrix} P_{8,1} \\ P_{8,2} \end{matrix}\right) P_9 P_{10} P_{11}$$

$$P_o = P_t \begin{bmatrix} P_{6,1} \\ P_{6,2} \end{bmatrix} P_7 \left[\begin{matrix} P_{8,1} \\ P_{8,2} \end{matrix}\right) P_9 P_{10} P_{11}$$

$$P_o = P_s P_3 P_4 P_5 \begin{bmatrix} P_{6,1} \\ P_{6,2} \end{bmatrix} P_7 \left[\begin{matrix} P_{8,1} \\ P_{8,2} \end{matrix}\right) P_9 P_{10} P_{11}$$

$$P_o = P_1 \begin{pmatrix} P_{2,1} \\ P_{2,2,1}\, P_{2,2,2}\, P_{2,2,3} \\ P_{2,3,1}\, P_{2,3,2} \end{pmatrix} P_3 P_4 P_5 \begin{bmatrix} P_{6,1} \\ P_{6,2} \end{bmatrix} P_7 \left[\begin{matrix} P_{8,1} \\ P_{8,2} \end{matrix}\right) P_9 P_{10} P_{11}$$

Figure 29. Hypothetical example for illustrating MSSM derivation.

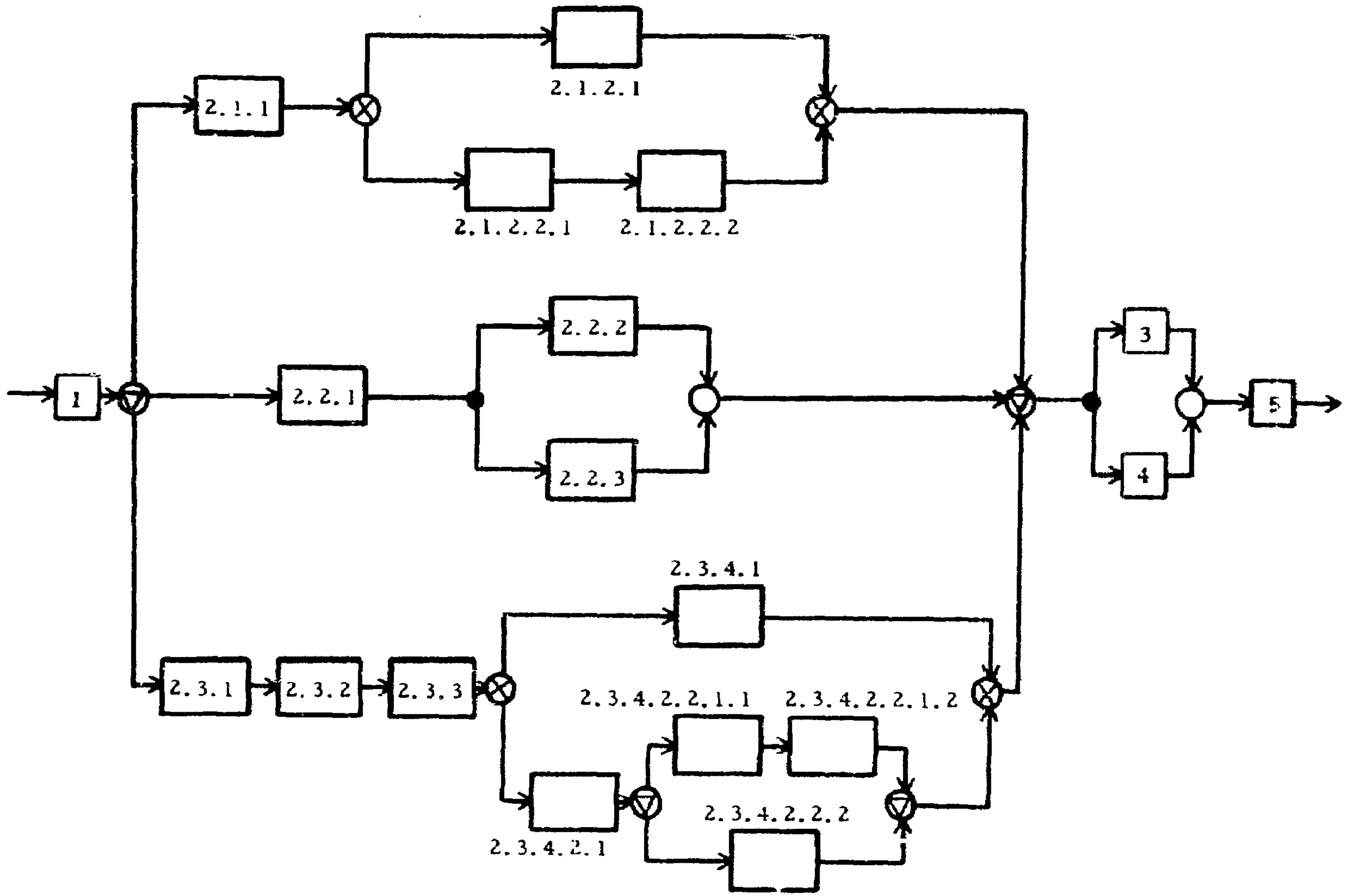


Figure 30. A hypothetical arrangement of PEF Units.

Step 2 (Cont'd.)

e. An example

Referring to the MSSM in Figure 29, first digits would be assigned as follows:

1 (2) 3 4 5 [6] 7 (8) 9 10 11

Observe that every number within first level parentheses or brackets has the same first digit. Second digits --referring to parallel groupings --would only be assigned to 2, 6, and 8, as follows:

1 (2.1; 2.2; 2.3) 3 4 5 [6.1; 6.2] 7 (8.1; 8.2] 9 10 11

Third digits --referring to a series within an alternative group --are assignable only to the second set, as follows:

1 (2.1; 2.2.1, 2.2.2, 2.2.3; 2.3.1, 2.3.2) 3 4 5 [6.1; 6.2]
7 (8.1: 8.2] 9 10 11

Double check that there are as many identification numbers as PEF Units in the GSSM. Another double check is to place numbers having different digits in the second place in brackets and compare the pattern against the MSSM. For example:

$$1 \begin{pmatrix} 2.1 \\ 2.2.1;\ 2.2.2;\ 2.2.3 \\ 2.3.1;\ 2.3.2 \end{pmatrix} \ 3\ 4\ 5 \ \begin{bmatrix} 6.1 \\ 6.2 \end{bmatrix} \ 7 \ \left(\begin{matrix} 8.1 \\ 8.2 \end{matrix} \right] \ 9\ 10\ 11$$

(Other examples are presented in the section on Allocation.)

Step 3

If the GSSM is large and complex, and if an immediate attempt is made to relate the probability of the output to that of the input, errors in constructing the MSSM are likely to occur. To minimize such errors, divide the GSSM into manageable groups of PEF Units, and assign dummy reference letters to the states between groups. Then, starting at the beginning of the GSSM, write the series of equations relating the output of each group to its input state by applying the two rules appropriately.

Step 4

After the entire series of equations is written for the system, start with the last equation and perform the following operation repeatedly until no dummy reference letters appear in the equation relating P(out) to P(in), always keeping P(out) on the left side of the equation. That is done by substituting for each reference letter probability its equivalent value, as determined in a prior equation.

The equations accompanying the GSSM in Figure 29 illustrate the application of the steps listed in the preceding section.

IV. ALLOCATION

A. Introduction

A primary goal of TEPPS is to provide a means of allocating system effectiveness requirements among discernible system operations[1] and thereby establish performance standards for those operations. This section is concerned with the procedure for deriving probability and time standards for identified personnel/equipment functional units of a system. The derived standards will thus represent a set of requirements on each PEF Unit such that the overall SER can be met.

Allocated standards differ conceptually from capability data; care should always be taken to keep in mind the distinction between them if accurate interpretations and conclusions are to be made from the outcome of the allocation process. There exist very few reliable human capability data involving either probability alone or probability and time to perform a given activity. If they were available, such data would have been determined experimentally by having observed many persons performing the same act many times and recording accomplishment times. The results would be a probability density function (over time) with known mean and standard deviation.

The process of allocating standards does not require human capability data nor does it imply man's capability to meet those standards; rather, the process establishes performance levels which must be reached for the associated SER to be met. To derive those standards, TEPPS utilize activity indices which are estimated to reflect the relative probability of accomplishing the various acts. By using many judges' estimates, density functions of indices over time have been generated so as to be able to specify the most reasonable requirements on PEF Unit accomplishment.

The computational process by which standards are derived from the indices would be tedious and error prone if done manually. Therefore, it is assumed that the analyst will be able to use a computer and the TEPPS program to accomplish the goals of allocation. However, in order to establish the most accurate interpretation of results, the

[1] It should be kept in mind that operations (i.e., PEF Units) are derived from analyses of system states. A PEF Unit or set of alternative PEF Units, is defined by its input and output states. Thus, allocation may be viewed as the process of determining elemental system states and deriving probability and time standards for achieving those states.

procedures below will explain briefly some of the computer operations for utilizing input data to derive standards. With this information and a calculator, an analyst can allocate to a limited number of PEF Units, if a computer were not available and if the SER included no time component.

B. Procedures

The data used for allocation are:

- Overall SER components: probability, P_0, and, when applicable, time, T_0. Also, any effectiveness requirements specified for any lesser portion(s) of the system.
- The GSSM, used for (1) the description of activities, and (2) deciding upon the mode of analyzing alternatives.
- The MSSM, which can aid in establishing the type and number of entries to go into the computer.
- Data Store entries for I (the index of task accomplishment), T_{min} and T_{max} for each activity shown in the GSSM. (See items 3 and 4 on page 14.)

Step 1

Observe whether the SER specifies a time component (T_0'). If it does, go to Step 2; if not, omit Steps 1 through 3, and start with Step 4 omitting references to time.

Step 2

Examine the GSSM closely and estimate T_e, the sum of the times required for interim activities (if any) not indicated on the GSSM. For example, T_e would include (1) time to walk from one console to another, (2) times to interact with other personnel or equipment because of the unique nature of the specific system context, where time data for the activities are not available, and (3) in general, times for a man to make whatever movements may be required in the real-life situation to initiate a PEF Unit activity after the occurrence of its input state, as specified in the GSSM.

Step 3

Determine T_0 from the following relation

$$T_0 = T_0' - T_e$$

where T_0' is the SER-specified time value, and T_e is the estimate made in Step 2.

Step 4

Gather all remaining data: (1) effectiveness requirements, (2) PEF Unit GSSM-representation numbers, (3) associated PEF Unit identification numbers from the Data Store, and (4) Data Store information, i.e., index and time values.

Step 5

Punch all necessary data cards according to the formats presented in Section V.

Step 6

To reduce computer operating time, and to simplify evaluation of allocated standards, select only one or two of the alternatives of greatest interest from among each set of alternative paths designated by an input circle-with-cross (or left parenthesis in the MSSM). In other words, lay aside the cards holding identification numbers of transition equivalent alternatives not to be included in the first run.

Step 7

Arrange data cards according to the format described in Section V.

Step 8

Feed data and program to computer.

Step 9

If it is desired to examine allocations based on other parenthetical alternatives (input circle-with-cross), insert the cards in the appropriate location in the original deck and remove other previously examined members of the same alternative set. A general description of the computer operations is included in Appendix A.

C. Computer Operations and An Example

In order to demonstrate application of the procedures and how the computer operates on the data, reference will be made to the relatively simple skeletal GSSM shown in Figure 31.

Note that identification numbers are shown as subscripts of the indices (I), minimum times (T_m), and maximum times (T_M), from the Data Store. The same subscripts are also used to identify the probability (p) and time (t) standards which are to be allocated. In Figure 31, it may be noted that (1) a single digit in the subscript is used when the PEF Unit is not part of an alternative set, and (2) within an alternative set, the first digit represents the number designated to the entire set, the second digit represents the "route" number within an alternative set, and the third digit represents the order within a particular "route."

Assume that the analyst is primarily interested in the alternative routes designated by 3.1 and 3.2.1, 3.2.2, so that examination of the other two alternatives is temporarily postponed. (If all three alternatives are included in the analysis, allocation throughout the system will be based on the most demanding one — i.e., the one with the lowest index of accomplishment.) The MSSM thus reduces to the following:

$$P_o = p_1 \begin{pmatrix} p_{2.1} \\ p_{2.2} \end{pmatrix} \begin{bmatrix} p_{3.1} & \\ p_{3.2.1} & p_{3.2.2} \end{bmatrix} p_4$$

where each of the p values on the right are allocated. The computer readout will provide each of the seven p values, as well as allocated times.

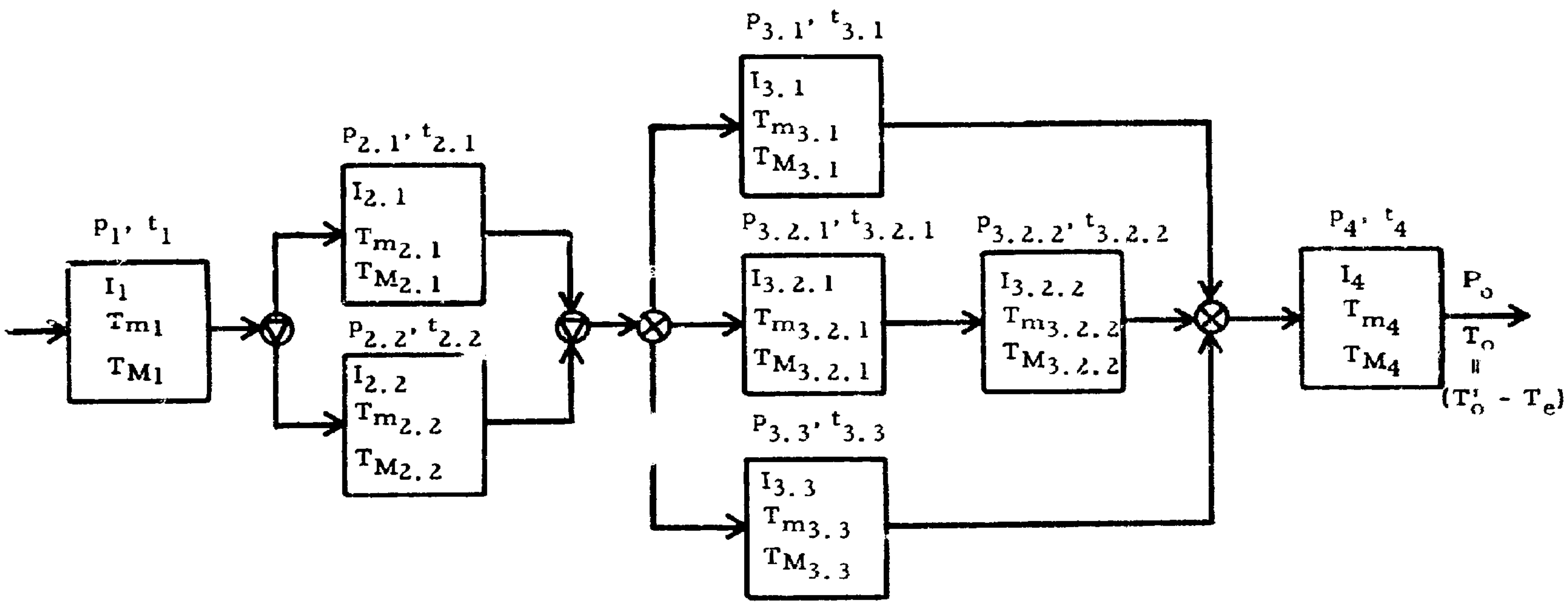
In essence, the computer will look at each product combination separately; that is, the computer will solve for p values in the following equations based on the requirement that $T_o = t_1 + t_2 + t_3 + t_4$:

$$P_o = (p_1)(p_{2.1})(p_{3.1})(p_4) \quad (1)$$

$$P_o = (p_1)(p_{2.2})(p_{3.1})(p_4) \quad (2)$$

$$P_o = (p_1)(p_{2.1})(p_{3.2.1})(p_{3.2.2})(p_4) \quad (3)$$

$$P_o = (p_1)(p_{2.2})(p_{3.2.1})(p_{3.2.2})(p_4) \quad (4)$$



<u>MSSM</u>

$$P_o = p_1 \begin{pmatrix} p_{2.1} \\ p_{2.2} \end{pmatrix} \begin{bmatrix} p_{3.1} & \\ p_{3.2.1} & p_{3.2.2} \\ p_{3.3} & \end{bmatrix} p_4$$

$$T_o = t_1 + t_2 + t_3 + t_4$$

T_m = minimum times

T_M = maximum times

Figure 31. Hypothetical skeletal GSSM for illustrating allocation.

Allocations will be made from among the different values for the same p and t such that P_o and T_c requirements are always met.

If T_o is less than the sum of the maximum times (or if T_o' is not specified), then p values can be found by applying the general equation (5).

$$p_j = k + (1-k) I_j \tag{5}$$

where j is a subscript referring to a particular PEF Unit, and k is a constant. Equation (5) is used to substitute k and I values in equations (1), (2), (3), and (4) for the right hand p_j values. For example, equation (1) is rewritten as follows:

$$P_o = [k + (1-k)I_1]\ [k + (1-k)I_{2.1}]\ [k + (1-k)I_{3.1}]\ [k + (1-k)I_4] \tag{6}$$

After solving equation (6) for k, each p_j can be found from equation (5).[1] Note that after performing those steps for all four equations, there will be four values of p_1 and p_4, and two values of all the others. The allocated probability for each PEF Unit will be its highest values from among those computed for all four equations.

If time is to be allocated also, the computer operations are much more complex. Since it is very unlikely that a solution will be attempted without a computer, those operations are not relevant to this section. However, the equations can be found in Appendix A.

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[1] The same procedure is followed for the similar equations derived from equations (2), (3), and (4). It is likely that each equation will yield a different value for k.

V. INPUT REQUIREMENTS AND OUTPUT CHARACTERISTICS OF TEPPS COMPUTER PROGRAM

A. Introduction

To present the information in this section, it is necessary to define what is meant by "chains" and "segments" in a GSSM. A "chain" is defined as a set of PEF Units for which effectiveness requirements are specified prior to the analysis. A "segment" is defined by time constraints, i.e., when effectiveness requirements on time are specified without corresponding probability requirements. Both concepts will be explained with reference to Figure 32, a hypothetical GSSM which will serve as an example for this section.

It should be noted that TEPPS Computer Program was originally written in FORTRAN IV for IBSYS version 13.9, to be run on the IBM 7094 computer. It is estimated to require approximately 0.1 second per PEF Unit in a single chain for the computer to perform all necessary computations to allocate probability and time standards and record results on tape.[1]

B. PEF Unit Designations and the Definition of a "Chain"

PEF Unit number designations were derived according to the procedures on page 62. Designation elements are generated according to series (elements in odd-numbered locations) and parallel (elements in even-numbered locations) positioning of a PEF Unit in the GSSM.[2] In Figure 32, the PEF Unit designated as

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[1]Information covering the availability of TEPPS Computer Program may be obtained from Psychological Research Branch (PERS A-32), Personnel Research Division, Bureau of Naval Personnel, Washington, D.C. 20370

[2]It may be noted that the dot, or AND, symbol is treated as a series-specifying condition; i.e., the segments to the right of the dot can be considered the same as if those segments were laid end-to-end.

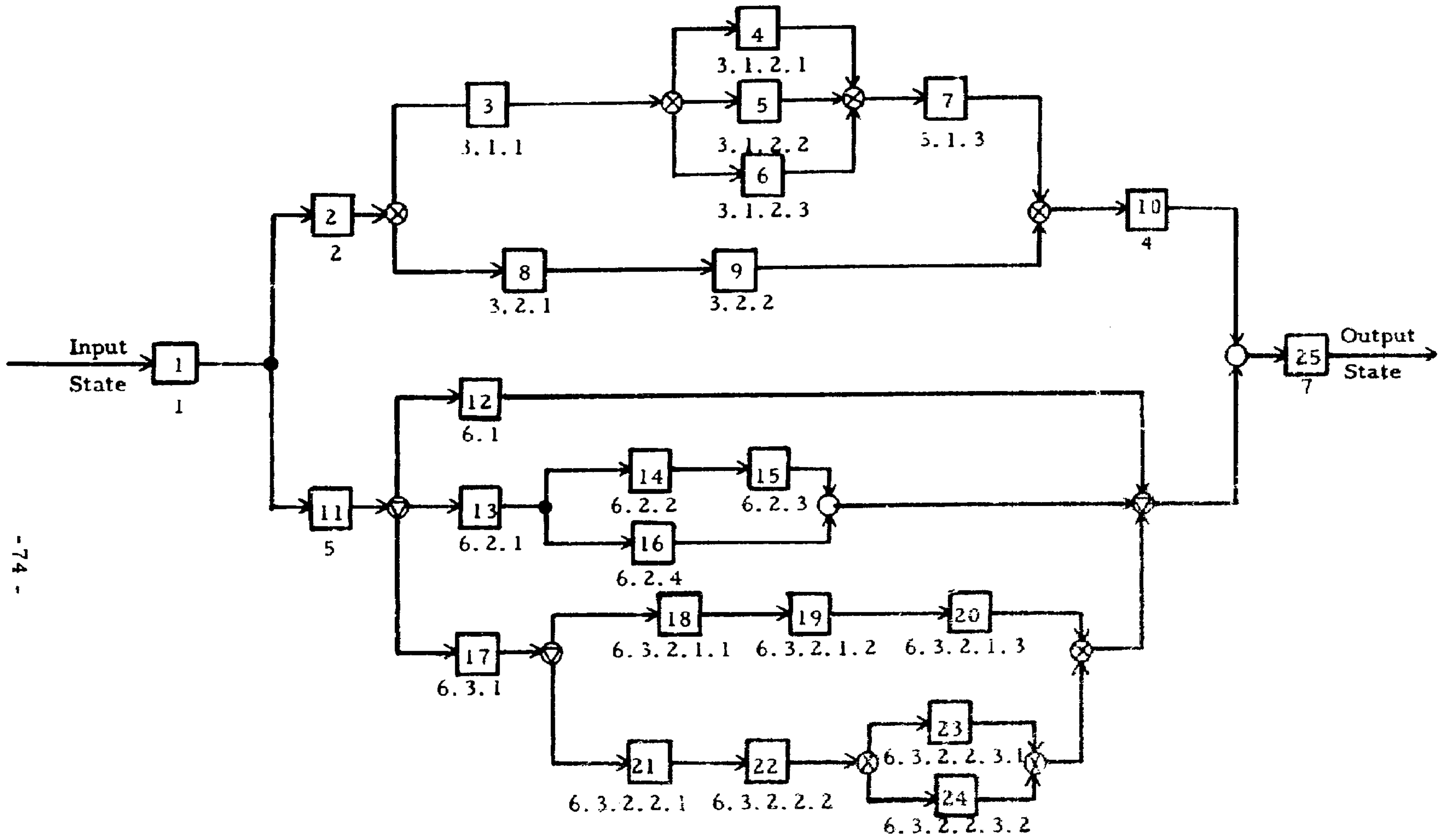


Figure 32. Hypothetical GSSM

Numbers within squares are reference numbers. Outside squares are the number designations for describing the GSSM structure. A number between two dots is called a designation element.

6.3.2.1.2 can be identified as follows: Reading the digits in reverse order, the PEF Unit is second in a series (the last "2" is element No. 5, i.e., in an odd-numbered location) of two or more PEF Units; that series is first among an alternative set of two or more series; the entire alternative set is second in a series with one or more other PEF Units or sets; that larger series is the third of several alternative series; and the larger set of alternatives provides for the sixth transition which must occur to reach the system output state.

If only an overall SER is specified for the system represented in Figure 32, then the GSSM can be seen to contain 20 "chains," of which the following are samples:

1 - 2 - 3.1.1 - 3.1.2.3 - 3.1.3 - 4 - 5 - 6.2.1 - 6.2.2 - 6.2.3 - 6.2.4 - 7
1 - 2 - 3.2.1 - 3.2.2 - 4 - 5 - 6.3.1 - 6.3.2.1.1 - 6.3.2.1.2 - 6.3.2.1.3 - 7
1 - 2 - 3.2.1 - 3.2.2 - 4 - 5 - 6.3.1 - 6.3.2.2.1 - 6.3.2.2.2 - 6.3.2.2.3.2 - 7

Using the reference numbers (<u>within</u> the PEF Unit squares) the chains can be listed so that they are perceived more readily. The above three can be rewritten as follows:

1 - 2 - 3 - 6 - 7 - 10 - 11 - 13 - 14 - 15 - 16 - 25
1 - 2 - 8 - 9 - 10 - 11 - 17 - 18 - 19 - 20 - 25
1 - 2 - 8 - 9 - 10 - 11 - 17 - 21 - 22 - 24 - 25

Assume, now, that the eight PEF Units with the initial two digits 6.3 (Units 17 through 24) have a requirement, $R_{6.3}$, specified for it, in addition to the overall SER of R_0. The extra requirement reduces the number of "chains" to 15. To illustrate how the reduction arises, and to keep the example simple, it will be assumed that only the elements 3.2 are selected from the upper alternative group. That leaves the following six chains:

1 - 2 - 8 - 9 - 10 - 11 - 12 - 25
1 - 2 - 8 - 9 - 10 - 11 - 13 - 14 - 15 - 16 - 25
1 - 2 - 8 - 9 - 10 - 11 - 25
17 - 18 - 19 - 20
17 - 21 - 22 - 23
17 - 21 - 22 - 24

It can be seen that chains are groups of PEF Units for each of which standards can be derived. For example, if the summation rule holds for the "R" Standards, then the MSSMs corresponding to the six chains would be:

$$R_o = R_1 + R_2 + R_8 + R_9 + R_{10} + R_{11} + R_{12} + R_{25}$$

$$R_o = R_1 + R_2 + R_8 + R_9 + R_{10} + R_{11} + R_{13} + R_{14} + R_{15} + R_{16} + R_{25}$$

$$R_o - R_{6.3} = R_1 + R_2 + R_8 + R_9 + R_{10} + R_{11} + R_{25}$$

$$R_{6.3} = R_{17} + R_{18} + R_{19} + R_{20}$$

$$R_{6.3} = R_{17} + R_{21} + R_{22} + R_{23}$$

$$R_{6.3} = R_{17} + R_{21} + R_{22} + R_{24}$$

In the third equation, allocation to elements in the chain is based on the difference between two known requirements. Note that a complete pathway from system input to output is not represented in the last four equations, since the 6.3 group -- which has its own effectiveness requirement -- is treated as a kind of autonomous subsystem.

C. Definition of a "Segment"

A chain is split into segments when at least one of its component PEF Units (or set of PEF Units) is constrained by a time requirement without a corresponding probability requirement. If a chain contains no such PEF Units the chain and its single segment are identical.

As an example, assume that Units 21 and 22 in Figure 33 are together constrained to be performed within T seconds. Also, assume that the eight PEF Units with the initial two digits 6.3 (#17 through #24) are constrained by the probability requirement, $P_{6.3}$, and time limit, $T_{6.3}$. As before, then, there are three chains defined by the latter requirements:

17 - 18 - 19 - 20
17 - 21 - 22 - 23
17 - 21 - 22 - 24

In addition, the second two chains comprise two segments each, so that the three chains are split as follows:

- Chain n — Probability = $P_{6.3}$

  Segment 1 — Time = $T_{6.3}$

  17 - 18 - 19 - 20

- Chain n + 1 — Probability = $P_{6.3}$

  Segment 1 — Time = $T_{6.3} - T$

  17 - 23

  Segment 2 — Time = T

  21 - 22

- Chain n + 2 — Probability = $P_{6.3}$

  Segment 1 — Time = $T_{6.3} - T$

  17 - 24

  Segment 2 — Time = T

  21 - 22

D. Another Hypothetical GSSM

In order to illustrate the input-output requirements of TEPPS Program, the simpler GSSM shown in Figure 33 will be used. That GSSM served as the "system" on which the computer program was actually originally tested.

The following effectiveness requirements were assumed:

1. An overall probability (P_o) of achieving the system output within time, T_o:

   $P_o = 0.86 \qquad T_o = 170$ seconds

2. Probability and time constraints on unit [3, 4, or 5] and unit 6:

   $P_{2.1.(2,3)} = 0.96 \quad T_{2.1.(2,3)} = 24$ seconds

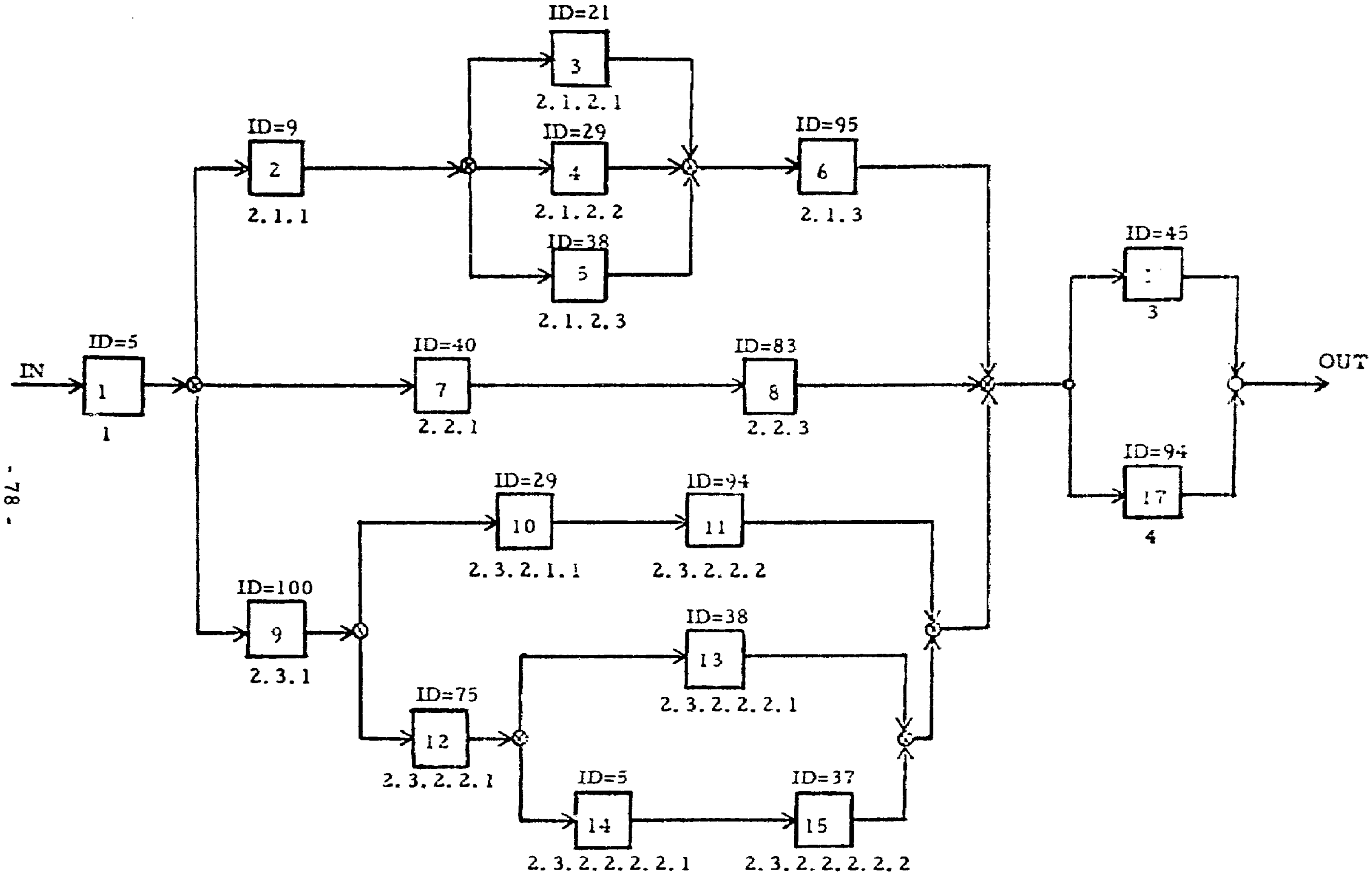


Figure 8. Another hypothetical GSSM.

3. Probability and time constrains on units 9 through 15:

$$P_{2,3} = 0.94 \qquad T_{2,3} = 80 \text{ seconds}$$

4. A time constraint on unit 12:

$$T_{2,3,2,2,1} = 9 \text{ seconds}$$

5. A time constraint on unit 16:

$$T_3 = 40 \text{ seconds}$$

6. A time constraint on unit 17:

$$T_4 = 40 \text{ seconds}$$

As a result of the imposed conditions, nine chains and their component segments can be identified as shown in Table III.

Table III. Chains and Segments in the Example

(Entries are the numbers lying inside the squares in Figure 33.)

Chain	Segments		
	1	2	3
a	1-2	16	17
b	1-7-8	16	17
c	1	16	17
d	3-6		
e	4-6		
f	5-6		
g	9-10-11		
h	9-13	12	
i	9-14-5	12	

As will be seen, the computer output identifies chains with reference to the probability-time effectiveness requirements imposed on the system, rather than by letters, as was done in Table III.

E. Input Data for the Program

There are eight sets of data cards required by the program. These will be described in the sequence in which they must occur following the program deck. Note that the odd-numbered card "sets" --as well as the last one-- contain only one card. Sets #2, #4, and #6 must contain at least two cards.

#1 $DATA punched in the first five columns of the first card. (One card only.)

#2 Activity Description Cards

(All relevant Data Store information for all activities in the GSSM: these must be arranged in increasing Activity I. D. order. From this set the program uses only those corresponding to the ones specified by each PEF Units' Activity I. D. in set #4, below.)

Each of these cards contains numerical Data Store information; currently, that information consists of the following:

(a) Activity I. D. (identification number) in columns 2 through 5.

(b) IOTA (I_j) in columns 6 through 14.

(c) Minimum time (T_{min_j}) in columns 15 through 23.

(d) Maximum time (T_{max_j}) in columns 24 through 32.

EXAMPLE: Assume that the Data Store contains 100 activities. Thus, there will be 100 cards in this set; the first three and the last one might appear as shown in Figure 34.

#3 Terminator Card
(One card only.)

This card has any non-zero integer punched in the first column. It is used to signal the computer that there are no more Activity Description cards.

#4 Network Description Cards
(Number of cards equals number of PEF Units in GSSM.)

Each card represents one PEF Unit. It contains the number designation from the GSSM, plus the PEF Unit's Activity

Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33 34 ... 80
Card 1					1		0	.	9	0	0	0						2	0	.	0					1	0	0	.	0			Observe CRT...
Card 2					2		0	.	9	0	3	2						4	5	.	0					2	7	0	.	0			Knowing all...
Card 3					3		0	.	9	2	4	5						2	7	.	5					3	3	0	.	0			Connect ...
.					.			.												.									.				
.					.			.												.									.				
Card 100			1	0	0		0	.	9	9	9	9							2	.	0					5	.	0	0	0			Push button...
		Activity I.D.					IOTA Values											T_{min}								T_{max}							Verbal Description, if Desired

Figure 34. Activity Description Cards for the example.

IDentification number from the Data Store. Elements in the GSSM number designation appear in order with the first designation element in columns 2 and 3, the second in columns 5 and 6, the third in columns 8 and 9, and so on through column 66. Each element in the number designation must lie between 1 and 99, inclusive. The Activity I. D. is punched in columns 69-72.

EXAMPLE: The PEF Unit having the number designation 2.3.2.2.1 (or #12) is assumed to be activity number 75 in the LAMA Data Store. Thus, the data card for this PEF Unit would be punched as shown in Figure 35.

Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	...	69	70	71	72	73	...	80
Punched Data			2			3			2			2			1					7	5			

Figure 35. One of the Network Description Cards in the example.

In the GSSM of Figure 33 there are 17 PEF Units. Thus, after the first "Terminator Card" there would be 17 Network Description cards. Although they need not be in order, it helps later interpretation if cards are arranged in increasing order according to number designations (numbers inside the squares in Figures 32 and 33).

5. Terminator Card
(One card only, with a non-zero integer punched in the first column.)

Same as #3. This card signals the computer that there are no more Network Description cards.

6. Probability-Time Cards (P-T Cards)

(One pair of cards for the SER and one pair for each ER to be imposed on any one or a group of PEF Units within the system.)

These cards are arranged in successive pairs. The first card of each pair identifies the particular group for which an ER is specified; that is, the first card lists the initial number designation elements common to all PEF Units in the group of interest. For the total system, the first card is entirely blank.

When values are appropriate for the first card, however, then the first element of the number designation is punched in columns 2 and 3, the second in columns 5 and 6, and so on through column 66; this is the same format as used in the Network Description cards (but without Activity I. D.).

The second card of each pair has the same format as the first card for the first 58 columns. On this card, the numbers in columns 2 and 3, 5 and 6, etc., are the elements which follow those appearing on the first card; they delimit the subgroups within the group for which probability and time standards have been specified. Elements on the second card are unrelated to one another, but each are related to (they actually follow...) the elements on the first card of the pair. For the entire system, columns 1 through 58 on the second card will be blank.

In addition, columns 59 through 67 of the second card contain the probability component of the ER, and columns 68 through 76 contain the time component, both including decimals. (If no decimal is included, the computer will automatically put one between the digits in columns 62 and 63, and between those in columns 71 and 72.)

EXAMPLE: Twelve P-T cards are needed to specify the effectiveness requirements listed on pages 77 and 79. The six pairs of data cards are illustrated in Figure 36. The second pair deserves special attention.

Since there are three groups of PEF Units beginning with 2.1, and since only two of the three are specified to lie within a requirement, the subgroups are indicated on the second card. Thus, the second pair of P-T cards delimits the requirements of all Units beginning with 2.1.2 and 2.1.3, and thereby omits 2.1.1 (and 2.1.4, 2.1.5, etc., if they existed).[1]

---

[1] It may be noted that requirements could be specified for a non-adjacent set of units, e.g., the requirements on the second pair of P-T cards could have referred to sets beginning 2.1.1 and 2.1.3. Requirements can be specified for either adjacent or non-adjacent series units which do not lie in an alternative set. For example, if there were two more units in series following #16 and #17, so that they would be designated as 5 and 6, effectiveness requirements associated with elements 1, 5, and 6 would be indicated by (a) leaving the entire first card blank --thereby indicating to the computer that reference is made to the main-line of the system-- and (b) punching 1 in the third column, 5 in the sixth column, and 6 in the ninth column of the second card of the pair, along with probability and time requirements.

Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	...	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	...
1st Pair				(Entire card blank)																																
				(Blank through column 59)																0	.	8	6	0	0	0		1	7	0	.	0	0			
2nd Pair			2			1																														
			2			3														0	.	9	6	0	0	0			2	4	.	0	0			
3rd Pair			2			3																														
				(Blank through column 59)																0	.	9	4	0	0	0			3	0	.	0	0			
4th Pair			2			3			2			2			1																					
				(Blank through column 59)																										9	.	0	0			
5th Pair			3																																	
				(Blank through column 59)																									4	0	.	0	0			
6th Pair			4																																	
				(Blank through column 59)																									4	0	.	0	0			

Figure 36. Pairs of Probability-Time (P-T) Cards for the example.

#7 Terminator Card
(One card only.)

Same as for #3 and #5, except that the numbers 8 and 9 have a special significance. The card signals the end of the probability-time cards and also indicates to the computer what to expect next. The computer interprets any digit in the first column except 8 or 9 to mean that there are absolutely no more data. If the number 9 appears in the first column, the computer is triggered to go back to the beginning of the program and start again, so it seeks data sets #2 through #7, as if to analyze different GSSMs. The number 8 in the first column triggers the computer to return to #4; by using this signal, different configurations of alternatives can be analyzed for the same GSSM, referring to the same activity ID information as before.

#8 End of File Card
(One card only.)

Usually, this card contains $EOF in the first four columns. This signals the computer that there are absolutely no more data cards (or any other cards) to be read.

F. Output

The computer internally assigns sequential reference numbers to the PEF Units, starting with 1, according to increasing GSSM number designations. Those assigned numbers correspond to the numbers which appear inside the squares in the GSSMs of Figures 32 and 33.

The program generates three sets of output information in the following order:

#1 Tables of Input Data

Two tables are presented summarizing the relevant data fed into the computer. The first lists the system PEF Units with their identification numbers and their corresponding IOTA, T_{min} and T_{max} values (see Table IV). The second summarizes the data on the pairs of Probability-Time Cards (see Table V).

Table IV

-----------------NETWORK-DESCRIPTION CARDS SORTED ON SUBSCRIPTS--------------------

CARD NO.	SUBSCRIPTS	ACTIVITY ID'S	ACTIVITY PARAMETERS I	TMIN	TMAX
1	1	5	0.999500	2.0000	6.5000
2	2 1 1	9	0.994500	4.0000	11.0000
3	2 1 2 1	21	0.996400	6.0000	12.5000
4	2 1 2 2	29	0.999800	1.0000	3.0000
5	2 1 2 3	38	0.960100	4.0000	13.5000
6	2 1 3	95	0.991300	8.5000	17.5000
7	2 2 1	40	0.998000	4.5000	9.0000
8	2 2 2	83	0.999000	4.0000	9.5000
9	2 3 1	100	0.951700	17.5000	210.0000
10	2 3 2 1 1	29	0.999800	1.0000	3.0000
11	2 3 2 1 2	94	0.997800	12.0000	52.5000
12	2 3 2 2 1	75	0.996400	5.0000	12.0000
13	2 3 2 2 2 1	33	0.960100	4.0000	13.5000
14	2 3 2 2 2 2 1	5	0.999500	2.0000	6.5000
15	2 3 2 2 2 2 2	37	0.999200	4.0000	9.0000
16	3	45	0.998700	24.5000	54.0000
17	4	94	0.997800	12.0000	52.5000

Table V

PROBABILITY-TIME CARDS SORTED ON SUBSCRIPT SEQUENCES

(FIRST LINE OF EACH PAIR CONTAINS SUBSCRIPTS---SECOND CONTAINS MODIFIERS)

CARD NO.	SUBSCRIPTS - MODIFIERS	CONDITIONS PROBABILITY	CONDITIONS TIME
1	.. ..	0.860000	170.0000
2	2 1 .. .. 2 3	0.960000	24.0000
3	2 3	C.940000	80.0000
4	2 3 2 2 1	-0.	9.0000
5	3	-0.	40.0000
6	4	-0.	40.0000

#2 Standards, by Individual Chains and Segments

Effectiveness requirements are allocated to PEF Units lying within referenced chains and segments. Chains and segments are listed according to the Probability-Time Card from which they are derived (as specified by "Card No." in Table V). Table VI presents the data for the first, second, fourth, and ninth chains exactly as they are printed out by the program. The remaining five chains have the same form (they are not included in order to conserve space).

#3 Standards Satisfying All Imposed Effectiveness Requirements

The results detailed in the above Output Set #2 are summarized in two tables, both containing essentially the same information. In the process of allocating to the components of each chain, the computer determines the maximum probability and minimum time standards from among all the standards assigned to each PEF Unit. At the end, then, the computer prints those values according to "Element Number" (Table VII) and then again according to "Activity I. D." (Table VIII).

The first table lists the standards for PEF Units as they occur in the GSSM. However, an activity may occur more than once in the operation of a system, and it may be of interest to know the standards for <u>activities</u> directly, rather than for their orientation in the GSSM. Thus, the second table lists probability and time standards according to activity.

G. Special Considerations

Certain precautions need to be observed for the computer to function within the bounds of the assumptions underlying the method by which standards are derived.

1. Increasing error will accrue if the effectiveness requirement on probability for a chain is much greater than the IOTA for any one component PEF Unit. Resulting allocated probability standards are likely to be so close to 1.0 that they will be indistinguishable.

2. For any segment, the effectiveness requirement on time should never be much less than the sum of the T_{min} values of the component PEF Units. If the sum of T_{min} is large relative to the time requirement, then the probability standards for the component PEF Units will tend to be equal, independent of their IOTA values.

Table VIa

P-T CARD 1 CHAIN 1 ASSIGNED PROBABILITY 0.895833

P-T CARD 1 SEGMENT 1 TIME CONDITION 56.0000

SEGMENT IOTA-PRODUCT 0.994003

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
1	0.999500	27.8061
2	0.994500	38.1939

P-T CARD 5 SEGMENT 2 TIME CONDITION 40.0000

SEGMENT IOTA-PRODUCT 0.737035

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
16	0.737035	40.0000

P-T CARD 6 SEGMENT 3 TIME CONDITION 40.0000

SEGMENT IOTA-PRODUCT 0.968785

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
17	0.968785	40.0000

Table VIa (Continued)

P-T CARD 1 CHAIN 1

CHAIN ASSIGNMENTS

ELEMENT NUMBER	IOTA	ASSIGNED PROBABILITY	ASSIGNED TIME (SEC.)
1	0.999500	0.999824	27.8061
2	0.994500	0.998069	38.1939
16	0.737035	0.907672	40.0000
17	0.966785	0.989040	40.0000

Table VIb

P-T CARD 1 CHAIN 2 ASSIGNED PROBABILITY 0.860000

P-T CARD 1 SEGMENT 1 TIME CONDITION 90.0000

SEGMENT IOTA-PRODUCT 0.996503

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
1	0.999500	33.9210
7	0.998000	23.9921
8	0.999000	32.0860

P-T CARD 5 SEGMENT 2 TIME CONDITION 40.0000

SEGMENT IOTA-PRODUCT 0.737035

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
16	0.737035	40.0000

P-T CARD 6 SEGMENT 3 TIME CONDITION 40.0000

SEGMENT IOTA-PRODUCT 0.968785

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
17	0.968785	40.0000

Table VIb (Continued)

P-T CARD 1 CHAIN 2

CHAIN ASSIGNMENTS

ELEMENT NUMBER	IOTA	ASSIGNED PROBABILITY	ASSIGNED TIME (SEC.)
1	0.999500	0.999761	33.9210
7	0.998000	0.995045	23.9921
8	0.999000	0.999523	32.0868
16	0.737035	0.874469	40.0000
17	0.968785	0.985099	40.0000

Table VIc

P-T CARD 2 CHAIN 1 ASSIGNED PROBABILITY 0.960000

P-T CARD 2 SEGMENT 1 TIME CONDITION 24.0000

SEGMENT IOTA-PRODUCT 0.762126

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
3	0.896688	10.1296
6	0.849934	13.8704

P-T CARD 2 CHAIN 1

CHAIN ASSIGNMENTS

ELEMENT NUMBER	IOTA	ASSIGNED PROBABILITY	ASSIGNED TIME (SEC.)
3	0.896688	0.983530	10.1296
6	0.849934	0.976076	13.8704

Table VId

P-T CARD 3   CHAIN 3   ASSIGNED PROBABILITY 0.940000

P-T CARD 3   SEGMENT 1   TIME CONDITION   71.0000

SEGMENT IOTA-PRODUCT   0.413229

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
9	0.427106	57.4742
14	0.983798	5.5023
15	0.983444	8.0235

P-T CARD 4   SEGMENT 2   TIME CONDITION

SEGMENT IOTA-PRODUCT   0.845061

SEGMENT ASSIGNMENTS

ELEMENT NUMBER	IOTA	TIME (SEC.)
12	0.845061	9.0000

Table VId (Continued)

P-T CARD 3 CHAIN 3

CHAIN ASSIGNMENTS

ELEMENT NUMBER	IGTA	ASSIGNED PROBABILITY	ASSIGNED TIME (SEC.)
9	0.427106	0.954266	57.4742
12	0.845061	0.987631	9.0000
14	0.983798	0.998707	5.5023
15	0.983444	0.998678	8.0235

Table VII

ASSIGNED ACTIVITY TIMES AND PROBABILITIES SATISFYING ALL CHAIN CONDITIONS LISTED ACCORDING TO ELEMENT NUMBER

ELEMENT NUMBER	ACTIVITY ID	PROBABILITY	TIME (SEC.)
1	5	0.999854	5.5023
2	9	0.998069	38.1939
3	21	0.983530	10.1296
4	29	0.999327	2.6366
5	38	0.994439	9.5881
6	95	0.983460	13.8704
7	40	0.999045	23.9921
8	93	0.999523	32.0868
9	100	0.957229	47.9095
10	29	0.999327	2.6366
11	94	0.990910	29.4540
12	75	0.987631	9.0000
13	38	0.994439	9.5881
14	5	0.999854	5.5023
15	37	0.998678	8.0235
16	45	0.923421	40.0000
17	94	0.990910	29.4540

Table VIII

ASSIGNED ACTIVITY TIMES AND PROBABILITIES SATISFYING ALL CHAIN CONDITIONS LISTED ACCORDING TO ACTIVITY I.D.

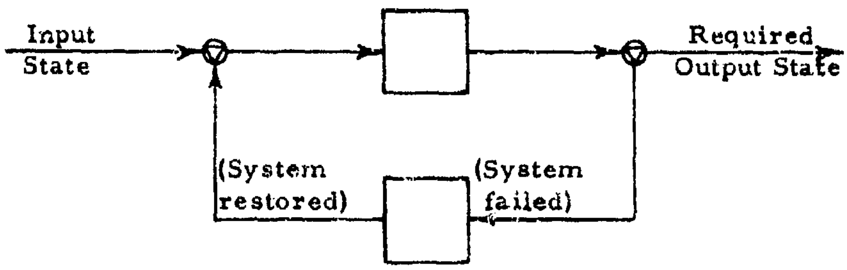
ACTIVITY ID	PROBABILITY	TIME (SEC.)
5	0.999854	5.5023
9	0.998069	39.1949
21	0.983530	10.1296
29	0.999327	2.6366
37	0.998678	8.0235
38	0.994439	9.5881
40	0.999045	23.9921
45	0.923421	40.0000
75	0.987631	9.0000
83	0.999523	32.0868
94	0.990910	29.4540
95	0.983460	13.8704
100	0.957229	47.9095

VI. ESTABLISHING STANDARDS FOR CORRECTIVE MAINTENANCE

A. Introduction

The general approach to establishing corrective maintenance performance standards is to allocate overall system or equipment maintenance time requirements to general categories of maintenance actions required to restore the system or equipment following a failure. Only performance-time standards are applicable to corrective maintenance tasks since it is assumed that the probability of successfully completing each maintenance task is equal to unity.[1]

Since a system failure potentially constitutes the output state of any personnel/equipment functional unit, the occurrence of a maintenance task can be incorporated in the graphic system state sequence model as illustrated below:



Due to the fact that the probability of failure and the associated maintenance need only be introduced at the most general level of modeling, it is not necessary to include failure and maintenance considerations in the detailed graphic and mathematical state sequence models used to represent operator performance. However, the graphic state sequence model defines the physical limits of the system or equipment for which maintenance time standards are to be established.

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1 The probability of completing maintenance subtasks (e.g., fault isolation, disassembly, etc.), however, are not necessarily equal to unity. When subtask errors do occur, they have the effect of lengthening overall task-time.

1. Source System Effectiveness Requirements

System effectiveness requirements constituting the source of corrective maintenance time requirements are availability or dependability requirements associated with the type of mission the system or equipment must perform. Two of the most common measures are point availability and dependability. Point availability is the expected probability that a repairable system or equipment will be operating (non-failed) to any random point in time. Dependability is the probability of successfully completing a mission of a specified duration providing that in the event of failure, downtime will not exceed a specified duration. Mathematical definitions for those and other measures appropriate to a wide variety of Navy missions are given in Table IX.

Once the availability or dependability measure is specified and system or equipment reliability is determined, the requirement for overall maintenance-time is uniquely established. As an illustration, if the point availability (A_p) requirement is 0.99 and the mean time between failures (MTBF) is 100 hours, mean time to restore (MTTR) is calculated:

$$A_p = \frac{MTBF}{MTBF + MTTR};\ 0.99 = \frac{100}{100 + MTTR};\ \text{and MTTR} = 1.01 \text{ hours}$$

2. Allocation

Given an overall MTTR requirement, the next task is to allocate times for completing general categories of maintenance actions required to restore the system or equipment. This is done using: (1) an expression relating (a) overall MTTR, (b) failure rates for various portions of the system or equipment, and (c) maintenance times for those portions; and (2) a basis for time allocation. The relation among system or equipment MTTR, failure rates and times for general categories of maintenance actions is given by:

$$MTTR = \left(\sum_{i=1}^{n} \lambda_i \bar{R}_i \right) \Big/ \sum_{i=1}^{n} \lambda_i \qquad (1)$$

where:

$\bar{R}_i$ = required mean time to carry out the ith category or type of maintenance (i.e., maintenance-time standard for the ith category of maintenance)

Table IX

General Classes of Availability and Dependability Models

Effectiveness Measure	Type of Mission	Expression
Point Availability	Continuous operation, e.g., communications equipment, search radar, navigation, etc.	$A_p = \frac{MTBF}{MTBF + MTTR} = \frac{\mu}{\mu + \lambda}$ where: $MTBF = 1/\lambda$ = Mean Time Between Failures $MTTR = 1/\mu$ = Mean Time to Restore
Reliability or Probability of Survival	Continuous operation over a stated mission period, t_1, e.g., guided missiles, etc.	$P_s = e^{-t_1/MTBF} = e^{-\lambda t_1}$
Mission Availability	Refinement of reliability to take into account the probability of the system being available at the onset of the mission.	$A_m = A_p P_s = \frac{\mu}{\mu + \lambda} e^{-\lambda t_1}$
Dependability	Mission of a specified duration, t_1, with allowable downtime, t_2, e.g., navigation equipment, tracking radar, sonar, etc.	$D = e^{-\lambda t_1} e^{-\mu t_2}$
Mission Dependability	Refinement of dependability to take into account the probability of the system being available at the onset of the mission.	$D_M = A_p D$ $= \frac{\mu}{\lambda + \mu} e^{-\lambda t_1} e^{-\mu t_2}$

λ_i = failure rate of the portion of the system or equipment maintained with the ith category or type of maintenance; and

n = number of different categories or types of maintenance.

Equation (1) can be rewritten:

$$MTTR = \sum_{i=1}^{n} (\lambda_i/\lambda_t)\, \overline{R}_i = \tag{2}$$

or

$$MTTR = \sum_{i=1}^{n} C_i \overline{R}_i \tag{3}$$

where:

λ_t = $\sum_{i=1}^{n} \lambda_i$, the total failure rate of the system or equipment, and

C_i = λ_i/λ_t, the failure rate allocation coefficient.

Allocation is accomplished by first computing a Repair Index, RI:

$$RI = \sum_{i=1}^{n} C_i T_i \tag{4}$$

where:

T_i = a time index, where the ratio T_i/T_{i+1} is the ratio of expected times to perform the ith and ith + 1 categories of maintenance.

Next an allocation constant K is computed:

$$K = MTTR/RI \tag{5}$$

Equations (3) and (4) are combined with the use of equation (5):

$$K = \left(\sum_{i=1}^{n} C_i \overline{R}_i \right) \Big/ \left(\sum_{i=1}^{n} C_i T_i \right) \tag{6}$$

and maintenance time performance standards are computed from equation (6):

$$\overline{R}_i = KT_i$$

In carrying out the allocation as outlined above, the allocation coefficients may be calculated readily using system or equipment reliability data. Time indices have been derived from maintenance burden prediction data developed for the U.S. Navy Bureau of Naval Personnel.[1] The time indices are given in Table X together with the maintenance categories with which they are associated.

The maintenance categories are identified according to two design features which account for a major portion of variability in maintenance-time: (1) the functional level at which fault isolation features are effective; and (2) functional level of fault correction. (Functional levels, defined in Table XI, denote the physical/organizational hierarchical levels of electronic equipment.) The relation between those design features and maintenance-time follows from the effect they have on the extent of complex troubleshooting required of the technician. Built-in fault isolation features usually permit the technician to isolate faults by observing simple input-output relations. Below the level at which fault isolation features are effective, more complex diagnostic activities are generally required. Thus, the extent of required complex troubleshooting decreases as isolation features are provided at lower functional levels in the system or equipment hierarchy. Bracketing the extent of required complex troubleshooting in the other direction is the method by which faults are corrected. If fault correction is effected by replacing higher functional levels (through modular design), it becomes unnecessary to carry out fault isolation to the part, stage or subassembly levels.

B. Procedure

The steps required to establish corrective maintenance-time standards are illustrated with data for the AN/URC-32 Radio Set.

Step 1: Determine the System or Equipment MTTR Requirement

Determine the overall system or equipment MTTR by substituting numerical values of the system effectiveness requirement and system or

[1] Manheimer, B.H. et.al. Predicting the Corrective Maintenance Burden, Volume I: Prediction Study. Federal Electric Corp., Paramus, New Jersey, 30 April 1963. Those data in turn are based on maintainability prediction data given in MIL-M-23313A(SHIPS), Maintainability Requirements for Shipboard and Shore Electronic Equipment and Systems, 9 October 1963.

Table X

Maintenance Category Time Indices

Fault Correction Level	Level at which Fault Isolation Features are Effective	Time Index
Part	No isolation required[1]	0.66
	Part	1.43
	Stage	1.84
	Subassembly	2.07
	Assembly	2.23
	Unit	2.36
	Group	2.48
	Equipment	2.58
	No isolation features	2.83
Module Replacement (Subassembly, Assembly, or Unit)	No isolation required[1]	0.51
	Δ Functional Level[2] = 0	0.78
	" " " = 1	0.83
	" " " = 2	0.90
	" " " = 3	1.02
	" " " = 4	1.28
	" " " = 5	1.51

1 Fault isolated by observation of operating displays or through the use of automatic fault isolation equipment.

2 "Δ Functional Level" represents the number of functional levels between the level at which isolation features are effective and the level at which fault correction takes place. Thus if the assembly is the fault correction level and isolation features are effective at the assembly level, the Δ Functional Level is 0. If the subassembly is the fault correction level and isolation features are effective at the unit level, Δ Functional Level = 2.

Table XI

Functional Level Definitions*

NAME	Electrical Characteristics	Mechanical Characteristic	Analog Equip. Illustration	Digital Equip. Illustration
Part	Basic Unit	Not normally subject to disassembly	Resistor, capacitor	Resistor, capacitor
Stage	An active element plus associated parts	Usually not replaceable	Amplifier stage, detector stage	Logic unit, flip flop, gate, binary counter
Subassembly	A portion of a subassembly	Element replaceable as a whole	IF strip, terminal board	Collection of logic units
Assembly	Performs a specific function	Element replaceable as a whole	Audio amplifier	Register, buffer
Unit	Capable of independent operation	May be replaceable	Power supply, radio receiver	Memory, arithmetic control
Group	Collection of units and assemblies which is not capable of performing a complete operational function	Not usually replaceable	Antenna group, indicator group	Indicator group
Equipment	Capable of performing a complete operational function	Not usually replaceable	Radio receiving set	Digital computer
Subsystem	Performs an operational function within a system	Collection of equipments, units, etc.	Communication system station	Tactical data system (one ship)
System	Performs an operational function	Two or more subsystems or equipments	Communication system	Tactical data system (entire net)

*Adapted from MIL-M-23313(SHIPS)

equipment reliability into the appropriate availability or dependability model (Table II). For example, if it is assumed that the System Effectiveness Requirements (SER) for the AN/URC-32 include a required point availability of 0.998 and that the equipment has an MTBF of 790 hours, the MTTR requirement is calculated:

$$A = \frac{MTBF}{MTBF + MTTR}; \; 0.998 = \frac{790}{790 + MTTR}; \; MTTR = 1.5 \text{ hours}$$

Step 2: Partition the System or Equipment into Maintenance Categories

The categories of maintenance considered in the allocation are listed in Table III and are identified by the functional level at which faults are corrected and the functional level at which fault isolation features are effective.

Partition the system or equipment into those maintenance categories by determining the system or equipment functional level breakdown. That is done by dividing the equipment or system into its various physical subdivisions, beginning with the highest subdivision and continuing down to levels such as parts, subassemblies, assemblies or units that will be replaced in corrective maintenance as illustrated in Figure 37.[1] Also determine the isolation levels or levels at which maintenance personnel can isolate the malfunction using designed test points or other built-in isolation features for each portion of the equipment. The isolation levels should be indicated on the functional level diagram as indicated in Figure 37. Identification of isolation and replacement levels as described above permits classification of various portions of the system or equipment according to the maintenance categories listed in Table X. Preparation of a functional level breakdown of the AN/URC-32 indicates that seven types of maintenance are performed on the equipment as indicated in Figure 38.[2]

Step 3: Determine the Failure Rate Associated with Each Maintenance Category

Determine the failure rates for portions of the system or equipment associated with each maintenance category using failure rate prediction

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[1] Construction of functional level diagram is covered in detail in MIL-M-23313A, p. 26 ff.

[2] Failure rate and functional level breakdown data for the AN/URC-32 were obtained from Manheimer, B.H. op. cit., 1963.

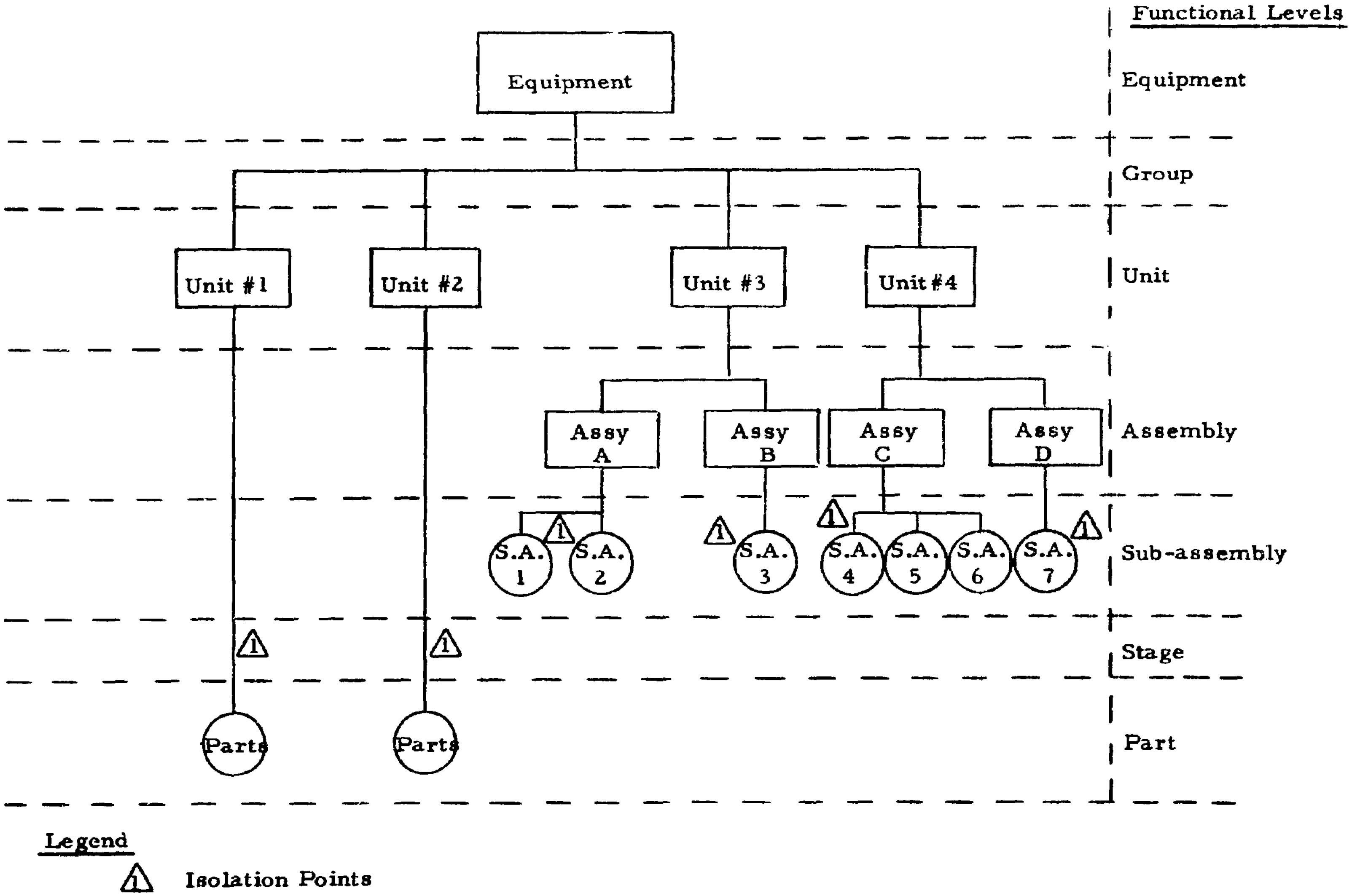

Figure 37. Illustrative functional level diagram.

MAINTENANCE TIME ALLOCATION FORM

(Entries are Failure Rates in Failures per 10^6 Hour)

EQUIPMENT AN/URC-32

EQUIPMENT PHYSICAL SUBDIVISIONS	PART REPLACEMENT									SUBASSEMBLY, ASSEMBLY AND UNIT REPLACEMENT						
	Isolation Level									Isolation Level						
											Functional Level					
	Not Req.	Part	Stage	Sub. Assy.	Assy.	Unit	Group	Equip.	None	Not Req.	0	1	2	3	4	5
Power Amplifier (Unit 2)			125.76													
Frequency Generator (Unit 3)				2.86							310.28					
Master Oscillator				76.26							149.24					
SB Generator (Unit 4)					40.68						272.82					
GW and FSK (Unit 5)						49.64										
Audio and Control (Unit 6)			2.86							26.08						
Frequency Comp[illegible]or (Unit 7)			28.20													
Handset Adapter (Unit 8)			11.92													
LV Power Supply (Unit 10)			26.82													
Blower (Unit 11)		2.85														
HV Power Supply (Unit 12)			131.12													
Other						10.00										
Category λ (Total λ = 1267.39)		2.85	326.68	79.12	40.68	59.64				26.08	732.34					
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
Category λ / Total λ	0	.002	.258	.062	.032	.047	0	0	0	.021	.578	0	0	0	0	0
Allocation Time Indices	.66	1.43	1.84	2.07	2.23	2.36	2.48	2.58	2.83	.51	.78	.83	.90	1.02	1.28	1.51
Time Standards (MTTR = 1.5)		1.72	2.21	2.48	2.68	2.83				.61	.94					

Figure 38. Maintenance time allocation for the AN/URC-32.

procedures.[1] Tabulate failure rates on the Maintenance-Time Allocation Form shown in Figure 38 by unit (or other convenient functional level) according to the type of maintenance performed. Sum those rates across all units to obtain a total failure rate for each maintenance category as shown in Figure 38. Divide the total failure rate for each maintenance category by the total failure rate for the system or equipment to obtain failure rate allocation coefficients, C_i.

The following failure rate data for the AN/URC-32 are obtained from Figure 38.

Type of Maintenance: Replacement Level	Type of Maintenance: Isolation Level	Maintenance Category Failure Rate	Failure Rate Allocation Coefficient (Category λ / Total λ)
Part	Part	2.85	C_2 = .002
Part	Stage	326.68	C_3 = .258
Part	Subassembly	79.12	C_4 = .062
Part	Assembly	40.68	C_5 = .032
Part	Unit	59.64	C_6 = .047
Module	Not Required	26.08	C_{10} = .021
Module	Δ Functional Level = 0	732.34	C_{11} = .578
			ΣC_i = 1.000

Step 4: Allocate Overall MTTR to Each Category of Maintenance

Allocate overall MTTR on the basis of the frequency of maintenance for each category and maintenance category complexity as follows:

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[1] Use NAVSHIPS 93820 (Method C or D) or MIL-HDBK-217. Other procedures are available for failure rate prediction at early points in the design cycle: see for example: Westland, R.A. and Hanifan, D.T. A Reliability-Maintainability Trade-Off Procedure for Navy Electronic Equipment, Dunlap and Associates, Inc., Santa Monica, California, June 1963, p. 3-125 ff.

a. Compute the Repair Index, RI:

$$RI = \sum_{i=1}^{n} C_i T_i$$

where C_i's are the failure rate allocation coefficients calculated in Step 3, and T_i's are the time indices given in Table III. Thus,

$$RI = 0.66\ C_1 + 1.43\ C_2 + 1.84\ C_3 + 2.07\ C_4 + 2.23\ C_5 + 2.36\ C_6 + 2.48\ C_7 + 2.58\ C_8 + 2.83\ C_9 + 0.51\ C_{10} + 0.78\ C_{11} + 0.83\ C_{12} + 0.90\ C_{13} + 1.02\ C_{14} + 1.28\ C_{15} + 1.51\ C_{16}$$

b. Compute the allocation constant K = MTTR/RI, where MTTR is the required system or equipment restore time determined in Step 1.

c. Compute the maintenance-time performance standards for each category or type of maintenance, $\overline{R}_i = KT_i$.

For the AN/URC-32, the following results are obtained by using the data given in Figure 38.

$$RI = 0.66(0) + 1.43(.002) + 1.84(.258) + 2.07(.062) + 2.23(.032) + 2.36(.047) + 2.48(0) + 2.58(0) + 2.83(0) + 0.51(.021) + 0.78(.578) + 0.83(0) + 0.90(0) + 1.02(0) + 1.28(0) + 1.51(0) = 1.25$$

The allocation coefficient is computed:

$$K = MTTR/RI = 1.5/1.25 = 1.2$$

The maintenance time performance standards are obtained by multiplying the allocation coefficients by K.

Type of Maintenance

Replacement Level	Isolation Level	Allocation Coefficient, C_i	Maintenance Time Standard, $\bar{R}_i$
Part	Part	1.43	1.72
Part	Stage	1.84	2.21
Part	Subassembly	2.07	2.48
Part	Assembly	2.23	2.68
Part	Unit	2.36	2.83
Module	Not Required	0.51	0.61
Module	Δ Functional Level = 0	0.78	0.94

It should be noted that the proportional adjustment carried out above in arriving at maintenance-time standards, is identical in approach to allocating standards to operator PEF Units when only probabilities of successful accomplishment are involved in the allocation.

VII. INTERPRETATION OF RESULTS

A. Introduction

There are basically two levels at which the results of TEPPS application can be interpreted:

- Comparisons between different sets of standards obtained by having looked at different patterns from among alternative sets of PEF Units; that is, the probability and time values themselves are meaningful when more than one of each is associated with the same PEF Unit.

- Comparisons between results and expectations of human performance capabilities, thus reflecting the adequacy of a particular personnel/equipment system design in meeting mission requirements.

B. Comparisons Among Different Sets of Standards

Figure 39 illustrates an example of the results of the allocation process when two alternatives are treated individually; for the situation depicted, the process produces two sets of standards for each PEF Unit which is not a member of a set of alternatives. The numbers in the illustration were generated for purposes of demonstration and are not founded on any actual values. The upper standards represent the outcome of omitting PEF Unit 2.2 from the data deck entered into the computer. The lower values result from omitting PEF Unit 2.1. It may be noted that if elements 2.1 and 2.2 were both entered into the computer, the emerging single set of standards would be as follows:

$p_1 = .975 \quad p_{2.1} = .90 \quad p_{2.2} = .99 \quad p_3 = .98$

$t_1 = 1.5 \quad t_{2.1} = 3 \quad t_{2.2} = 4 \quad t_3 = 2.5$

From these values, it can be seen that the .85 probability requirement is always satisfied -- or exceeded -- within the required time, eight minutes.

$$T_o = 1.5 + 3 + 2.5 = 7 \text{ or}$$

$$T_o = 1.5 + 4 + 2.5 = 8 \text{ and}$$

$$P_o = (.975)(.90)(.98) = .85 \text{ or}$$

$$P_o = (.975)(.99)(.98) = .945$$

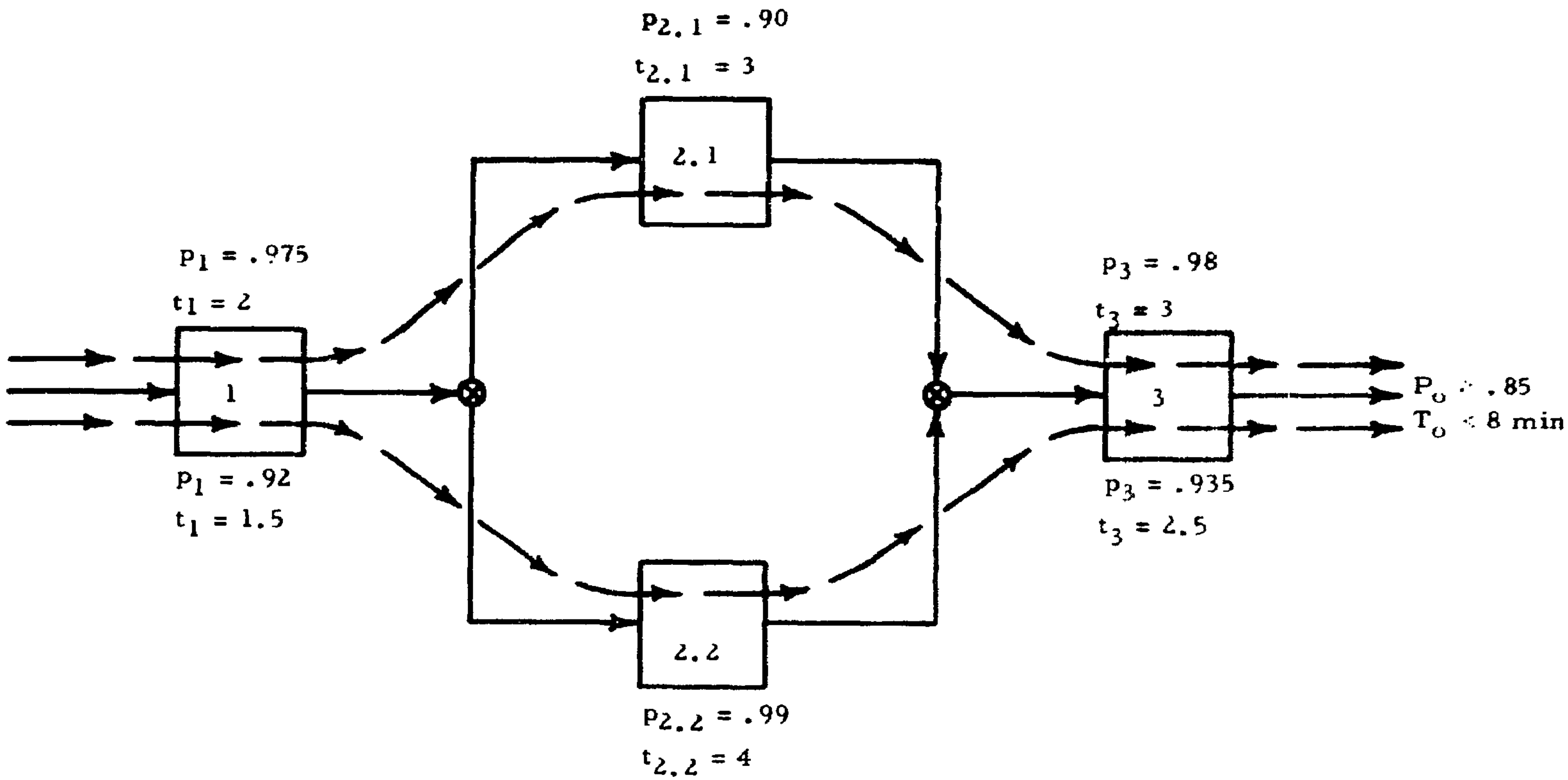


Figure 39. Hypothetical example of results when alternatives are considered individually.

Returning to the example in Figure 39 some comments can be made about the results without identifying any activities and without knowing about man's capabilities. The only knowledge available is that (1) three PEF Units are required to be performed in succession; (2) one of the three is either PEF Unit 2.1 or 2.2; and (3) the system makes it possible for the operator to select whichever alternative he wishes.

If the operator chooses to select 2.2 (or if he is forced to do so by an alteration in original system design) the probability requirements on PEF Units No. 1 and No. 3 become much lower than if 2.1 were used. Thus, if it is economically feasible and reasonable, it may be worth the effort to redesign the system so as to preclude performance of 2.1. As a result, more error could be tolerated in performing No. 1 and No. 3 if further investigation reveals that the higher demands made by 2.1 on No. 1 and No. 3 may be difficult to meet.

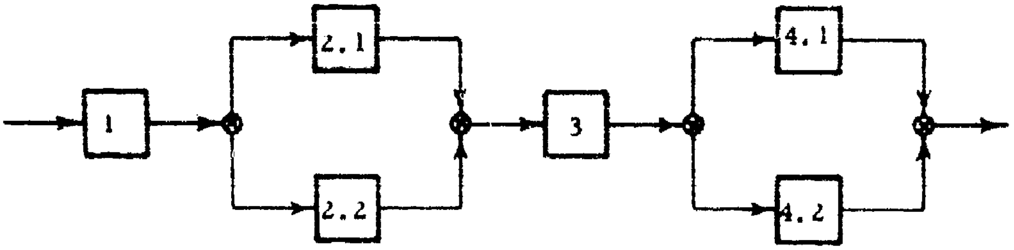
Consideration of time as well as probability allocations lead to the following questions which can be answered only through examination of human capability information:

For either alternative,

- Are the allocated times reasonable for achieving the associated probability of accomplishing the activities?
- If both alternatives are permitted (i.e., if the system stands as shown by the GSSM) is it possible to meet the more stringent time and probability standards?
- Is 2.2 more costly to implement than 2.1, and if so, is the trade-off to increase the likelihood of meeting the SER economically feasible and desirable?
- And particularly regarding these data, is there any specific reason for the system to permit the possibility of alternative operations having such divergent relative probabilities of accomplishment?

If evaluation of alternative routes yields essentially the same allocations throughout the system, it would be concluded that the alternatives are functionally equivalent and that no distinction need be made between them unless changes are to be made in the system. It is to be noted that even though a set of alternatives leads to the same allocation for a particular system configuration, that does not guarantee the same outcome for

another system configuration. For example, in Figure 40 assume that allocations to all PEF Units are the same when chains a_1 or a_2 are analyzed. That result does not necessarily indicate that chains b_1 and b_2 would yield the same allocation results.



Chains:

$a_1 = 1 \rightarrow 2.1 \rightarrow 3 \rightarrow 4.1$
$a_2 = 1 \rightarrow 2.1 \rightarrow 3 \rightarrow 4.2$

If these chains lead to identical allocated values for p_1, $p_{2.1}$, and p_3, with $p_{4.1} = p_{4.2}$ (same for time values),

$b_1 = 1 \rightarrow 2.2 \rightarrow 3 \rightarrow 4.1$
$b_2 = 1 \rightarrow 2.2 \rightarrow 3 \rightarrow 4.2$

it is not necessary that these chains lead to the same result

Figure 40. Illustration of a four-chain configuration of PEF Units.

C. Consideration of Human Capabilities

Once standards have been allocated to system PEF Units, the question arises as to how well those standards can be met. Two primary concerns are (a) interpreting results, and (b) obtaining indications of what to do about discrepancies. Since the fundamental goal of the technique is to aid in the development of the most effective, feasible system to accomplish the requirements of the mission assigned, it is necessary to find the optimal match between personnel performance levels required by a particular system design (standards) and the performance levels that can be expected from personnel being considered for assignment to that system.

For the method to be employed for that purpose, some form of personnel capability or expectancy data are required. S_c (for "capability standard") is the symbol used here to represent the probability with which a human can be expected to perform all system operations for which a system effectiveness requirement has been established. Corresponding to S_c is the system required value, P_0, symbolized by S_r (for "required standard").

It has been mentioned that at present, no comprehensive and fully reliable store of human performance capability data is available. In the absence of behavioral data store expectancies, however, capability data can be obtained on the specific personnel group being considered for assignment to the system by measuring the performance of that group on the PEF Units resulting from the standards derivation process. Another source would be proximate data obtained from previous studies of personnel operations that are comparable to those required by the system under analysis, if any can be found. A third source could be the combined estimates made by a number of knowledgeable, experienced field observers.

1. An Example

To illustrate the use of capability data, three hypothetical sets of probabilities have been generated and are presented in Table XII. Each set is to be interpreted as applying to a system represented by three functions (F_1, F_2 and F_3) such that F_1 is composed of three elements, and both F_2 and F_3 comprise four elements each. The three sets of values are totally independent and may be imagined to apply to three different systems, or as three mutually exclusive hypothetical possibilities for a single system. In any event, the non-parenthetical numbers represent the probabilities with which humans can be expected to perform the associated PEF Units, i.e., reliable human capability values. The numbers in parentheses are derived (calculated) values; those numbers represent required performance levels.

It is assumed that the MSSM for each Function is a simple multiplicative model, i.e., there are no alternative routes; thus, the product of the capability values for the elements in any one row in Table XII is equal to the number under S_c in that row. Similarly, the product of the associated parenthetical, allocated values in a single row equals S_r, the operational requirement. In most of the subsequent discussion, system operational requirements (S_r values) will be compared with the derived capability scores (S_c values); also, comparisons will be made between allocated and capability values at the PEF Unit level. The kinds of considerations and operations for the comparisons at the two levels are quite similar.

Three Hypothetical Sets of Performance Standards, Corresponding Capability Levels and the System Operational Requirements that Must be Met

Data Set	Function	Element 1	Element 2	Element 3	Element 4	Capability S_c	Required S_r
I	F_1	(.993)	(.988)	(.958)[1]	----		.940
		.983	.971	.895[2]	----	.854	
	F_2	(.984)	(.987)	(.979)	(.988)		.939
		.978	.983	.970	.986	.919	
	F_3	(.990)	(.988)	(.989)	(.983)		.951
		.982	.978	.980	.964	.907	
				System		.712	.839
II	F_1	(.957)	(.988)	(.994)	----		.940
		.965	.990	.995	----	.951	
	F_2	(.983)	(.973)	(.991)	(.991)		.939
		.998	.997	.999	.999	.993	
	F_3	(.993)	(.996)	(.985)	(.976)		.951
		.997	.998	.994	.991	.980	
				System		.925	.839
III	F_1	(.965)	(.986)	(.988)	----		.940
		.944	.976	.981	----	.904	
	F_2	(.992)	(.983)	(.971)	(.992)		.939
		.999	.998	.997	.999	.993	
	F_3	(.992)	(.981)	(.990)	(.987)		.951
		.991	.975	.986	.982	.936	
				System		.840	.839

1 Parenthetical numbers are derived allocated probabilities; e.g., note that (.993) (.988) (.958) = .940 = S_r for F_1 of Set I.

2 Expected probabilities of personnel performance obtained from capability data.

The three sets of hypothetical data (non-parenthetical values) were generated so that (1) in Set I, the S_r values exceed S_c values; (2) in Set II, all capability scores are larger than the corresponding required values; and (3) in Set III there is one high S_c probability and two S_c values that are below S_r, but the system values are about the same. It may be noted that the probabilities of accomplishing system output states are obtained by multiplying the three values directly above each of them; for example, in Set I,

System $S_r = [.940]\,[.939]\,[.951] = .839$ and

System $S_c = [.854]\,[.919]\,[.907] = .712$

2. Interpretation

Discrepancies between corresponding S_c and S_r values -- for any set of data -- may result from one or more of the following conditions:

a. Human capabilities differ from those required, and changes in skill levels or number of personnel are indicated through modifications in training or selection procedures.

b. One or more components of the System Effectiveness Requirement (SER) at one or more levels of specificity is incompatible with that which can be achieved for the system design used in the analysis.

   - A different system design could meet the requirements.

   - The criteria used for setting the SER do not correspond to that dictated by system context.

c. The SER, in combination with decision criteria, is set unrealistically high for any conceivable system design (or too low for the system to be useful).

d. Decision criteria used in the allocation process are unnecessarily stringent or do not correspond to actual system context requirements.

e. The system may not be appropriately modelled, either graphically, mathematically, or both.

For example, Set I might represent a system whose design may need to be modified if S_r cannot be reduced. Excluding for the moment the possibility of other bases for the discrepancies between S_r and S_c, each Function would need to be redesigned. That does not mean that the probability of accomplishing each element within a given function must be increased as a result of the redesign; it is conceivable that in producing a large increase in the probabilities of accomplishing some elements, others may be forced down. For example, the probability associated with Element 4 in F_2 might tolerate a reduction of .001 or .002 in order to increase the probabilities for accomplishing the other three elements.

Similarly, time allowances (where critical) may need to be altered by redesign in order to increase probabilities of accomplishment. As long as the system effectiveness specifications do not state requirements at the element level, reconstruction of the design at that level theoretically can assume any form. Of course, redesign must always take into consideration such additionally specified decision criteria as personnel training requirements and cost.

It is also conceivable that the original requirement of .839 is higher than needed in the system context. All other things being equal, if the system could actually serve its purpose by supplying a specified output with a probability of .700 (S_r = .700), then the values in Set I are satisfactory (S_c = .712).

Almost any effectiveness requirement (except absolute perfection) could be met if cost and time to realize the design were unlimited. However, restrictions on economy of all kinds normally set limits on what may reasonably be expected from a system. Considering the immense number of permutations and combinations of elements in a system, it is not a simple matter to specify a general procedure for determining the non-feasibility of achieving system requirements. The decision may have to rest in the hands of the responsible system designers who are unable to find alternative means of providing the required system output state. As a result, either the effectiveness requirements, the decision criteria, or both may need to be relaxed somewhat.

Just the reverse may be true for the system represented by the data in Set II of Table V where S_r is less than S_c. That condition could arise if the effectiveness requirement and/or decision criteria are more relaxed than the system mission actually requires. On the other hand, it may well be true that the system mission can in fact be accomplished successfully at the originally stated requirement level; $S_c > S_r$ might then

be the result of overdesign. An overdesign indicated by a large discrepancy between S_c and S_r generally corresponds to an expenditure of hardware or personnel (number or capabilities) greater than necessary, i.e., excess costs in general. Note, however, that it may be possible to trace overdesign to particular elements. For example, in F_1 of Set II, only Element 1 may be overdesigned while Element 2 and 3 appear to have very similar allocated and capability probability values. Similarly, the associated values in Element 2 of F_3 are almost identical.

When applying the technique to an existing system, it is in the best economic interests to investigate all possible sources of a difference between S_c and S_r before deciding upon a course of action. One source which has not been mentioned so far could lie not in the system, but in the basis of the decision that a discrepancy exists. That is, the system may not have been modeled accurately, so that an erroneous conclusion is drawn. It is likely that such errors will occur less and less frequently as experience is gained with the use of the technique. However, in the initial phases of its application, some means for double-checking the accuracy of the models may be necessary.

Considering Set III in Table XII it is evident that if no S_r values were specified at the Function level, the overall system effectiveness requirement of .839 could be met, as indicated by the results of the capability analysis (.840). However, Function requirements <u>are</u> indicated, and for two of the Functions (F_1 and F_3) the capability scores indicate inability to meet those requirements. That inability is particularly reflected in Elements 1 and 2 of F_1 and Elements 2, 3 and 4 of F_3. On the other hand, the ability to perform F_2 is much greater than specifications demand.

Conclusions and possible actions resulting from these findings are approached in the same way as has been discussed above where, for the entire system, all S_c values were higher or lower than S_r values. However, when some are higher and some are lower, it is less likely that the source of the discrepancies lies in erroneous modeling, unless there is some reason to suspect that the analyst is differentially treating some Functions with greater care or accuracy than others. Also, where the Function specifications are not all met, but system effectiveness requirements are, the added alternative exists to re-evaluate the basis for establishing requirements at the Function level. It may be less costly and serve the purpose of the mission to accept the overall system as it stands, rather than to seek a means of revising elemental PEF Units to meet the standards at the Function level.

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APPENDIX A

COMPUTER PROGRAMMING PROCEDURES

APPENDIX A

COMPUTER PROGRAMMING PROCEDURES

A. Introduction

TEPPS computer program procedures for allocating system effectiveness requirements among PEF Units defined in the GSSM are described here. As TEPPS methodology is refined and extended, the computer program will be updated to reflect those developments. However, highly flexible programming concepts have been employed to minimize the effort required to add or modify instructions to the computer. That effect is being achieved by designing a tree-like program having a basic, central set of "main program" operations, the majority of which involve sequential selection of appropriate subroutines.

B. Input

The first computer operations directed by the main program are the reading and storage of data, which consist of:

(1) the code numbers which identify activities in the Data Store, and the parameters (I, T_{min} and T_{max}) associated with each of those activities,

(2) identification numbers and associated Data Store code numbers of the PEF Units which appear in the GSSM and which are to receive allocation standards, and

(3) imposed effectiveness requirements.

The main program uses the identification numbers of the system-specific data to construct a functional representation of the GSSM in the computer. That representation is best visualized as being like an electronic switching network, with a selector switch at the input of every set of alternative PEF Units, i.e., wherever there is an input circle with cross or triangle symbol.

C. Operations

To look at every possible combination of alternative PEF Units, the main program summons the first subroutine named Locator. Locator identifies each "chain" to be evaluated. A "chain" is determined by the selection of a single PEF Unit from each of the alternative sets which have been fed to the computer as data. Every pattern from among alternatives, then, establishes a unique "chain" or series of activities.

The identified chain is then subjected to analysis under the direction of a second subroutine, Calc I. A primary characteristic of an isolated "chain" is that the probability of its output is the product of the probabilities of accomplishing its component PEF Units. Calc I. then, maximizes the product of the IOTA values associated with the PEF Units in the chain, under the constraint that the sum of the times to perform those units is T_0, the corrected overall SER on time (see Section IV, B).

each PEF Unit, according to equation (1).

$$i_j = \frac{I_j \int_{-3}^{z_j} e^{-1/2\, x^2}\, dx}{\int_{-3}^{+3} e^{-1/2\, x^2}\, dx} \qquad (1)$$

where:

i_j = the variable index for the jth PEF Unit

I_j = the LAMA Data Store's maximum IOTA for the jth PEF Unit

x = a dummy variable

$z_j = \dfrac{\log t_j - \mu_j}{\sigma_j}$

t_j = the time standard to be allocated to perform the jth PEF Unit

μ_j = $1/2\,(\log T_{max_j} + \log T_{min_j})$ or the mean of the logarithmic transformation of the i_j distribution over time

σ_j = $1/6\,(\log T_{max_j} - \log T_{min_j})$ or the standard deviation of the logarithmic transformation of the ij distribution over time.

The only constraint is that $\Sigma t_j \leq T_0$. If the sum of minimum times to accomplish activities is larger than T_0, then all of the

i_j values are set equal to zero, and each allocated probability (p_j) in the chain is set equal to the nth root of P_o (the SER probability component). That is, if $\Sigma T_{min} > T_o$, then $i_j = 0$ and $p_j = P_o^{1/n}$. The other extreme is also treated in a particular way; if $\Sigma T_{max} < T_o$, $i_j = I_j$, so that allocated probability values are derived directly from the IOTA listed in the LAMA Data Store.

To maximize $\prod_{j=1}^{n} i_j$, for n PEF Units in a chain, the computer calculates n equations of the form

$$\frac{i_j}{i_j'} = K \qquad (2)$$

where:

$$i_j' = \frac{di_j}{dt_j}$$

K = a constant whose value is determined by the n equations and the limitation that $\Sigma t_j = T_o$.

The resulting i_j and t_j values are stored in memory, and the main program is signalled that the Calc I subroutine has completed its job.

Calc II subroutine is then summoned to compute the alloc... p_j values such that $\prod_{j=1}^{n} p_j = P_o$. That is done by substituting for p_j the conversion relation of equation (3).

$$p_j = k + (1 - k)\, i_j \qquad (3)$$

In other words,

$$\prod_{j=1}^{n} [k + (1 - k)\, i_j] = P_o \qquad (4)$$

equation (4) is solved for k, and then each p_j is determined by applying equation (3) for every j.

When all p_j values have been stored, the computer signals the primary program, SUPR, which directs several subroutines to print out allocated p_j and t_j values along with identifications of their associated PEF Units. The program requests Locator subroutine to select another chain after which the cycle is repeated until all chains have been evaluated and the results recorded.

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13. ABSTRACT

This report is a procedural guide for the application of a Technique for Establishing Personnel Performance Standards (TEPPS). It specified the types of input data required, provides instructions and examples on how to proceed through the various steps in TEPPS's application and includes guidelines for interpretation of results. The TEPPS computer program procedures also are discussed along with instructions for use.

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